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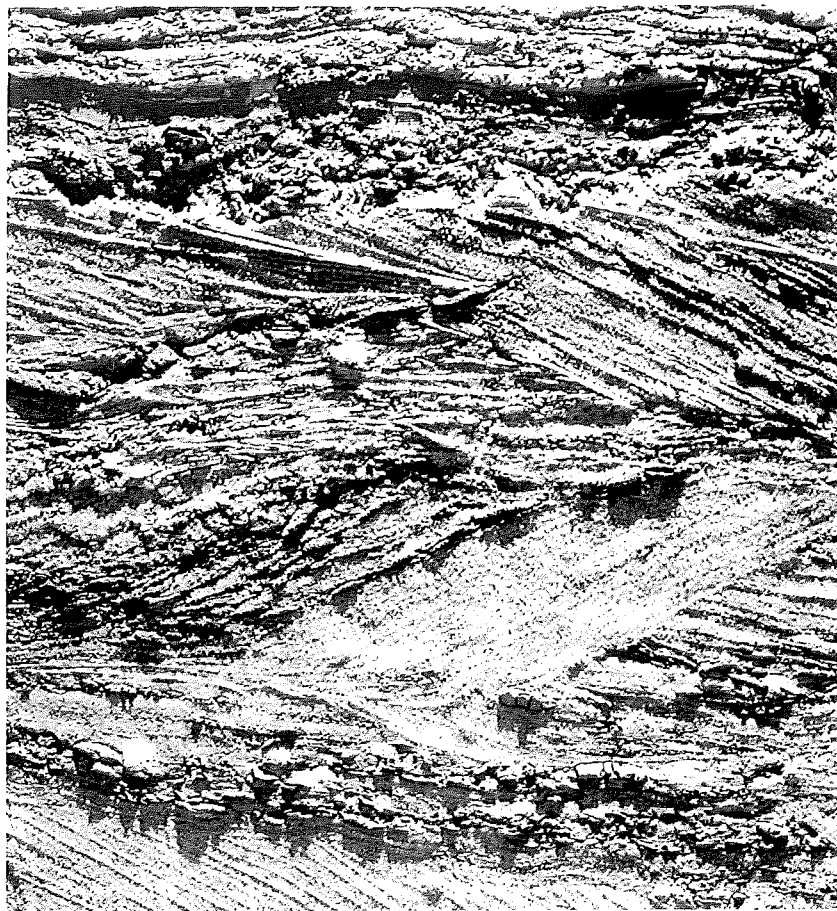
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EARLY-PLEISTOCENE TIDAL AND FLUVIATILE ENVIRONMENTS IN THE SOUTHERN NETHERLANDS AND NORTHERN BELGIUM



Kees Kasse

3. DEPOSITIONAL ENVIRONMENTS

3.1 Introduction

Until now facies studies of the Early-Pleistocene deposits in Noord-Brabant and northern Belgium have been scarce. Most investigations concentrated on local stratigraphical, palynological and sediment-petrographical aspects. The lack of paleoenvironmental information may, in part, be explained by the absence of fauna remains in the sediments. Only some deer antlers are known from the Campine Clay in northern Belgium (Germonpré, 1983). Molluscs and diatoms have not been found in the investigated area. Furthermore sedimentological analysis of exposures has been hampered by the predominantly clayey character of the deposits in Belgium. Therefore, the published ideas concerning the depositional environment of the Early-Pleistocene deposits range between a fluvial and a marine origin. Belgian investigators more often concluded a coastal origin, while in The Netherlands a fluvial genesis has in general been favoured.

The aim of chapter 3 is:

- 1: to summarize published ideas concerning the depositional environment and to evaluate different environmental interpretations (§3.2).
- 2: to describe and interpret the sedimentary structures and to reconstruct the depositional environments of the lithostratigraphic units defined in chapter 2 (§3.3).
- 3: to characterize the depositional environments by their paleobotanical content (§3.4).

The description and analysis of sedimentary structures is based on the study of lacquer peels from exposures and boring cores (fig. 3.1). Paleocological information, based on the analysis of pollen and macroscopic plant remains, is additionally used.

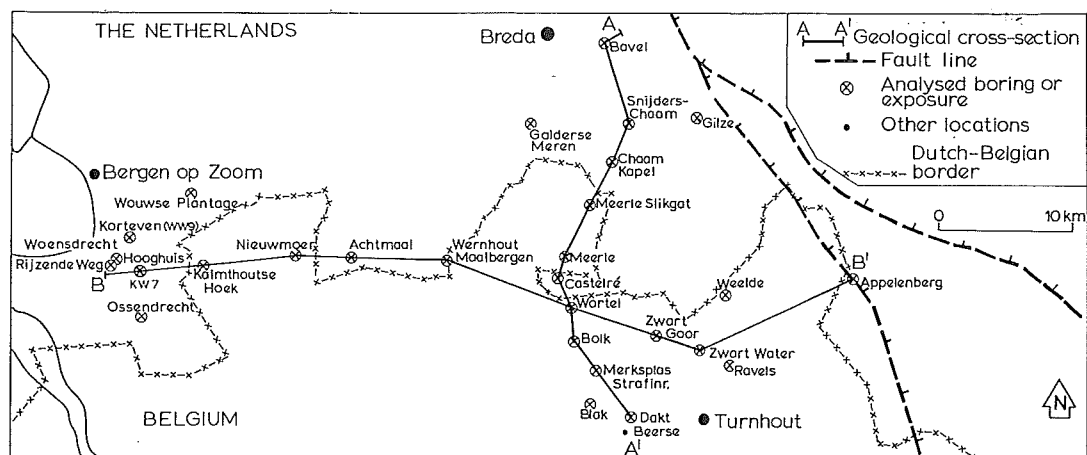


Fig. 3.1: Location map.

3.2 Historical review and discussion of former environmental interpretations

This paragraph presents a summary and discussion of articles published since 1950, in which an opinion is expressed concerning the sedimentary environments of the Early-Pleistocene deposits in Noord-Brabant and northern Belgium (see table 2.1). An extensive review of publications older than 1950 is given by Geys (1975).

In 1954 Tavernier interpreted the Mol Sands in Belgium ("Sables de Mol") as continental deposits. According to Tavernier, the overlying Campine Clays ("Argiles de la Campine") were deposited by westward flowing meandering rivers in a large alluvial plain. The clay-layers were formed in a backswamp environment, which was intersected by more sandy (gully) systems. Tavernier's interpretations were essentially based on geometrical similarities to recent alluvial plains.

One year later Doppert and Zonneveld (1955) correlated the Early-Pleistocene deposits in Noord-Brabant with the "Kedichem Series" in the central Netherlands on sediment-petrographical and lithological grounds. However, this correlation is incorrect since the deposits in Noord-Brabant belong to a large extent to the Tegelen Formation (our Turnhout-Rijkevorsel Members) (see §2.6). They stated already a priori (in the title of their publication) that the Pleistocene sediments in Noord-Brabant were deposited in a fresh water, fluviatile environment. They found that *Carya*, *Pterocarya* and *Tsuga* pollen was also present in deposits (so-called "Kedichem Series") younger than the Tiglian. They reinterpreted the pollen data from boring Oosterhout (Burck, 1953) and included them in the "Kedichem Series" instead of the Tiglian. This reinterpretation later proved to be only partly correct: Zagwijn and De Jong (1984) interpreted the lower pollen spectra again as Tiglian, while the upper spectra were regarded as representative of the Bavelian period.

Van Dorsser (1956) supported the ideas of Doppert and Zonneveld concerning the fluviatile origin of the Early-Pleistocene deposits in Noord-Brabant (our Woensdrecht Member), although she stated that the correlation of western and central Noord-Brabant is uncertain. Referring to earlier sediment-petrographical work by Nelson and Van der Hammen (1950), who in turn refer to Edelman (1933), she proposed a Meuse river system, which supplied stable heavy minerals to western Noord-Brabant during the Early-Pleistocene. Sands (locally homogenized) and overlying loams, in her opinion, had been deposited in braided and meandering river systems, during glacial and interglacial periods. However, the vertical and lateral relationships between the various deposits are not so clear in her work. The Early-Pleistocene sediments were regarded as one unit and they were used together in the reconstruction of the depositional environment. In our opinion it is more likely that different units are involved (see fig. 2.6). The sands with a stable heavy mineral association, which are described by Van Dorsser below a clay-layer at Hoogerheide (pit de Vijver), are part of our Woensdrecht Member. Sediments with a stable heavy mineral association above the clay-layer described at Langeschouw are probably part of our Gilze Member. Although these sediments are sediment-petrographically more or less identical they need not have been formed in the same depositional environment, nor be of the same age. The correlation from the central Netherlands to Noord-Brabant (Doppert and Zonneveld, 1955) and western Noord-Brabant (Van Dorsser, 1956) was essentially based on comparable heavy mineral sequences, which, however, are not isochronous by definition.

A fluviatile origin for the Early-Pleistocene deposits was also pro-

posed by Van Voorthuysen (1957), who studied the geology of western Noord-Brabant and the adjacent province of Zeeland. He introduced the fluviatile "Halsteren Deposits" (our Woensdrecht and Hoogerheide Members), which were found between "Icenian sands" and the Middle- to Late-Pleistocene "Vlissingen Deposits". The up to 80 m thick "Halsteren Deposits" filled a deep channel ("Zeeland Valley"), which was eroded into the underlying marine "Icenian sands" (modern Maassluis Formation). His idea of severe fluviatile erosion and deposition was later adopted by Van Rummelen (1965, 1970, 1972, 1978) in the geological survey of Zeeland.

In contrast with the ideas mentioned above, Dricot (1961) concluded that the Campine Clays around Beerse in Belgium (our Rijkevorsel and Turnhout Members) had been deposited in a salt-marsh environment. The fine sands underneath the clay were interpreted by Dricot as tidal flat deposits. The abundance of Chenopodiaceae pollen, the presence of Hystrichosphaeridae, Dinoflagellates, bioturbation by Polydora and heavy minerals of supposed northern origin (A-association) were used as arguments for a coastal origin of the deposits. However, his high Chenopodiaceae content of the deposits (up to 45%) was not confirmed by Greguss and Vanhoorne (1961) and Paepe and Vanhoorne (1970). Furthermore, Zonneveld (1948b) had already pointed out that an A-heavy mineral association is no proof for a marine Fenno-Scandian origin, as the Rhine supplied about the same heavy mineral association.

Intercalated between two clay-layers (our Rijkevorsel and Turnhout Members) Dricot found a sand-unit characterized by stable heavy minerals and a cold floral assemblage. He interpreted this so-called "Beersien" unit (our Beerse Member) as an eolian deposit formed in an arctic climate. De Ploey (1961), Paepe and Vanhoorne (1970) and Haest (1985) later confirmed Dricot's environmental interpretations of the Beersien sediments on palynological and granulometrical grounds.

In the same year De Ploey (1961) agreed with Dricot that the top of the Campine Clay (our Turnhout Member) is a salt-marsh deposit, underlain by tidal flat sediments with an unstable heavy mineral association. According to De Ploey, the clay-layer decreases in thickness to the north and a sandy tidal flat facies, deposited in an estuarine environment, becomes more important. De Ploey (1961) further described a sand-layer with a B-Limburg heavy mineral association (St. Lenaarts Formation), which occurred above the marsh-clay. He interpreted this sand-unit as a Weichselian, eolian deposit reworked by fluvial processes. Later Vandenberghe and Krook (1981) described a sand-layer ("Alphen Sands") with a stable heavy mineral association, overlying the Tegelen Formation in Noord-Brabant. In contrast to De Ploey they interpreted this unit as a braided river deposit of Early-Pleistocene age. However, in 1985 Haest again interpreted fluviatile sands with a stable heavy mineral association, resting on the Campine Clay at Beerse, as Early-Weichselian deposits. In the present study it is established on lithostratigraphical grounds that the St. Lenaarts Formation of De Ploey can be correlated with our Gilze Member ("Alphen Sands") of Early-Pleistocene age (fig. 2.5, 2.7).

Confusion is also possible between the "Beersien" deposits (our Beerse Member) and the St. Lenaarts Formation (our Gilze Member), since they have many sediment-petrographical and sedimentological characteristics in common, especially where the separating clay-layer (our Turnhout Member) is thin or absent. For instance, the Weichselian St. Lenaarts Formation at St. Lenaarts described by De Ploey (1961) was reinterpreted by Greguss and Vanhoorne (1961) and Paepe and Vanhoorne (1970) as the Early-Pleistocene Beerse Member.

During his pedological survey in western Noord-Brabant, Van Oosten

(1967) correlated a clay-layer (our Turnhout Member) with the salt-marsh clay-layer of De Ploey in adjacent Belgium. The occurrence of peat and wood fragments and cat-clay phenomena (acid sulphate soils) in the clay-layer and thinly laminated deposits below the clay were regarded by Van Oosten as indications of a fresh to brackish tidal environment. However, thin laminations are no proof of a tidal environment, but in combination with cat-clay phenomena his conclusions seem probable.

Paepe and Vanhoorne (1970, 1976) reinvestigated clay-pits around Beerse (Belgium) and confirmed the previous interpretations of Dricot (1961) and De Ploey (1961). The Early-Pleistocene deposits were subdivided into three lithological units. The lower clay-unit (Rijkevorsel Member) and the upper clay-unit (Turnhout Member) were interpreted as tidal flat deposits. However, the peat and vegetation remnants mentioned by Paepe and Vanhoorne (1970) are no proof of the tidal character of the Campine Clay. The regular alternations of clay and sand with opposed stream directions, which they found in gully-fill structures, are indeed a strong indication of a tidal environment. At the base of the Turnhout Member Paepe and Vanhoorne found a sand-layer with large-scale, low-angle, cross-bedding dipping to the northwest. They interpreted these structures as beach deposits, indicating the onset of the marine transgression of the Turnhout Member. They further described a sand-bed (Beerse Member) in between both clay-layers, which was characterized by soil horizons, frost wedges and cryoturbations. On sedimentological and palynological grounds they concluded that the Beerse Member was formed by eolian and fluvial processes in a cold climate. In 1975 and 1978 Geys returned to the previous environmental ideas of Tavernier (1954), Doppert and Zonneveld (1955) and Van Dorsser (1956). He concluded a fluvial origin of the Early-Pleistocene deposits. His interpretation was especially based on granulometric and quartz morphoscopic methods. Geys stated that his Early-Pleistocene Campine Clay Formation was deposited by a meandering river flowing to the westnorthwest. Stream energy was low in general and limnic sedimentary environments occurred locally. He extended the fluvial sediments into the "Halsteren Deposits" filling the "Zeeland Valley" described by Van Voorthuysen (1957). According to Geys this Early-Pleistocene river system resembled the Holocene river district of the central Netherlands, which is characterized by clayey backswamp environments and sand-filled gullies. In his emphasis on granulometric data, however, he disregarded the lithostratigraphic position of the sediments. He included different lithostratigraphic units in the Campine Clay Formation. Fresh water molluscs at Bavel (our Bavel Member), granulometric data of large-scale, cross-bedded sands above the Campine Clay (in Merksplas-Pampa; Wortel-Kolonie) (our Gilze Member), together with granulometric data of the Campine Clay deposits (our Turnhout and Rijkevorsel Member) were all forced into his meandering river depositional model. It is questionable whether granulometric and morphoscopic analysis alone are able to reveal depositional environments, as most of the sediments concerned are polycyclic. Short distance reworking of older sediments need not be expressed granulometrically or morphoscopically. Besides, certain granulometric parameters and methods used by Geys differentiate only between e.g. river sands and beach deposits (Sk-sigma diagram from Friedman). They should not be applied to distinguish between other depositional environments. Estuarine sediments for instance will always belong to the river sediment group, although they are not fluvial in a strict sense. The supposed geometrical similarity between the Early-Pleistocene deposits in Belgium (Geys: fig. 3.3.1.) and the sub-recent Holocene fluvial deposits in the central Netherlands (Geys: fig.

3.9.1.) is misleading. The sand occurrences around Meerle (our Gilze Member) have no genetic relation to the clay deposits more to the south (our Turnhout Member; boring Wortel), since they belong to different lithostratigraphic units (fig. 2.5) and formed in different periods (Eburonian and Tiglian respectively; see chapter 4).

In the same year Zagwijn and Van Staalduinen (1975) presented a lithostratigraphic scheme of the Quaternary formations in The Netherlands. The Tegelen Formation (including our Rijkevorsel, Beerse, Turnhout, Hoogerheide and Woensdrecht Members) and the Kedichem Formation (including our Gilze and Bavel Members) were described as fluvial deposits supplied by the Rhine, Meuse and smaller rivers from the south. The lower part of the Tegelen Formation was considered to be time-equivalent with the marine Maassluis Formation. The genetic element in this lithostratigraphic system can result in classification problems, which have been dealt with in §2.6.

Vandenbergh and Krook (1981) and Vandenbergh et al. (1986) investigated sedimentary sequences and structures in the coarse-grained "Alphen Sands" (our Gilze Member; Kedichem Formation). They concluded a braided river depositional environment. On sediment-petrographical and sedimentological grounds they suggested a southeast-northwest flowing Meuse, with smaller southwest-northeast oriented tributaries from Central Belgium.

Bisschops et al. (1985) interpreted the Tegelen Formation in eastern Noord-Brabant as a fluvial, deltaic deposit of the Rhine and Meuse with near-coastal facies in certain intervals. Smaller rivers from the south were locally important during the deposition of the Kedichem Formation. Fluvio-periglacial and eolian periglacial environments are mentioned by them. The Sterksel Formation according to Bisschops et al. (1985) was deposited by the river Rhine, during glacial and interglacial periods.

Haest (1985) reinvestigated the Beerse Member (between our Rijkevorsel and Turnhout Members). He found five soil-horizons in the Beerse sands, of which the lower four were deformed and contained associated frost-wedges and some small ice-wedges. His granulometric analysis of the Beerse sands pointed to an eolian depositional environment, with local surficial runoff.

3.3 Sedimentary environments based on the description and interpretation of sedimentary structures

3.3.1 Introduction

In this paragraph sedimentary environments of the members defined in chapter 2 are reconstructed, based on the study of the sedimentary structures in lacquer peels and large-scale lateral and vertical facies changes in two cross-sections. Sedimentary structures are described and subsequently interpreted as bedform structures and correlated with specific sedimentary environments according to especially Reineck and Singh (1980) and Reading (1980).

The locations of the analysed borings and exposures are presented in fig. 3.1. The legend of the sedimentary structures is given in fig. 3.2.

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






























	no visible structures		large-scale current ripple direction
	large-scale cross-bedding		small-scale current ripple direction
	large-scale low angle cross-bedding		bidirectional currents of equal importance
	large-scale trough cross-bedding		bidirectional currents, one current dominant
	parallel horizontal bedding		fining-upward sequence
	small-scale cross-bedding		coarsening-upward sequence
	small-scale trough cross-bedding		reactivation surface
	climbing ripple cross-bedding		clay-, silt-, peat-pebbles
	small-scale herringbone cross-bedding		reworked organic material
	wave ripple cross-bedding		fine gravel
	flaser bedding		weak - moderate - strong bioturbation
	wavy sand-clay bedding		charcoal pieces
	lenticular bedding		soil horizon
	wavy parallel bedding		humic
	crinkly bedding		roots
	wavy crinkly bedding		wedge structure
			deformed bedding

Fig. 3.2: Legend of sedimentary structures and additional symbols.

3.3.2 Rijkevorsel Member

Description of the sedimentary structures

Sedimentary structures in the Rijkevorsel Member are shown in fig. 3.3 and 3.4 in a north-south and east-west cross-section. Clay-pit Beerse Dakt is presented in more detail in fig. 3.5 and 3.6.

Four sedimentary units are distinguished within the Rijkevorsel Member. Unit A (fig. 3.3: Bolk) is a fining-upward sequence with massive and large-scale cross-bedded, medium coarse sand, grading into flaser bedded, fine sand with some bioturbation.

Unit B (fig. 3.3: Bolk, Wortel; fig. 3.4: Wernhout Maalbergen) consists predominantly of lenticular bedding, with opposed cross-bedded sand-lenses covered by clay-drapes.

Unit C (fig. 3.3: Bolk, Wortel; fig. 3.4) is characterized by large-scale cross-bedding, flaser bedding and local lenticular bedding (fig. 3.4: Achtmaal). Around Breda marine shell-fragments (*Cardium*, *Mytilus*) are present (see fig. 2.8).

Unit D (fig. 3.3: Bolk, Meerle Slikgat, Chaam Kapel; fig. 3.5: Beerse Dakt) is formed by a fining-upward sequence. Flaser bedding grades into locally bioturbated lenticular bedding (fig. 3.3, 3.5: Beerse Dakt, Meerle Slikgat) and massive bedding with local peaty soil horizons (fig. 3.3: Merksplas Straf., Beerse Dakt).

A lacquer peel (fig. 3.5) of units (B), C, D at Beerse Dakt illustrates various sedimentary structures in the Rijkevorsel Member. Lenticular bedding (B) changes upward into flaser bedding and some low-angle cross-bedding (coarsening-up)(C). From the middle of the peel a fining-upward sequence is reflected by an increase of lenticular bedding (D).

Interpretation

The frequent sand-clay alternations with sharp transitions and the herringbone cross-bedding are indications for tidal processes. Sand was transported by ebb and flood currents, while mud was deposited during slack-water periods (Terwindt, 1981).

Unit A is interpreted as a tidal channel-fill. Medium coarse sand with clay-pebbles and reworked organic material was deposited under the form of megaripples. Stream velocity reduced by channel migration and fine sand was deposited by small current ripples. During slack-water clay-flasers covered the current ripples.

Unit B: The lenticular bedding points to quiet tidal deposition. Mud-draped ebb and flood ripples indicate a subtidal environment (lagoon-al). These subtidal deposits locally overlay fluvialile sands and peat of the Merksplas Member (see fig. 2.7: boring 17E-154) indicating a sedimentary hiatus (see chapter 4: chronostratigraphy). Rapid drowning must have taken place.

Unit C: This sandy interval reflects more turbulent tidal conditions. The large-scale, low-angle cross-bedding and the flaser bedding were formed by megaripples and small current ripples in tidal channels. Coarse-grained channel sediment is rare however and clayey beds with lenticular bedding are present in unit C. This points to limited lateral channel migration, which is explained by the landward setting of the tidal depositional environment.

The absence of marine shells and the scarcity of bioturbation is an indication of a low salinity of the environment. A northward salinity increase is suggested by the presence of marine molluscs around Breda.

Unit D: The top of the Rijkevorsel Member is fining-upward. The flaser, wavy and lenticular bedding reflect the final stage silting of the previous tidal channels. Part of the channel infilling still occurred in subtidal situations (Meerle Slikgat), as both ebb and flood ripples are covered by slack-water mud.

The tidal sequence in the Rijkevorsel Member was well exposed in Beerse Dakt (fig. 3.5). The coarsening-upward sequence in the lower part of the lacquer peel reflects a gradual increase of tidal currents (transgression). The flaser and low-angle cross-bedding (in the middle) were formed in (pointbars of) small and shallow tidal channels (Reineck and Singh, 1980). The flaser and lenticular bedded couplets may have originated by seasonal cycles (Van den Berg, 1986), spring-neap cycles or variable weather and hydrological conditions.

Sub-horizontal coarser grained units in the middle of the lacquer peel, are interpreted as upper flow regime shallow water deposits. Current velocity diminished in the upper part of the lacquer peel and lenticular bedding was formed (fining-upward sequence). Ultimately, only clay was deposited, followed by plant growth.

Estimation of the tidal range

The tidal sequence at Beerse Dakt offers the opportunity to estimate the tidal range during the deposition of the Rijkevorsel Member (fig. 3.6). It is assumed that the gradual fining-upward sequence reflects the final silting of the area at a more or less constant sea-level stand. The mean low water (MLW) and mean high water (MHW) levels are fixed by the range of the sedimentary structures (fig. 3.6). MLW level is difficult to establish. The lower part of the lacquer peel was formed during a transgression (coarsening-up) with a rising sea-level.

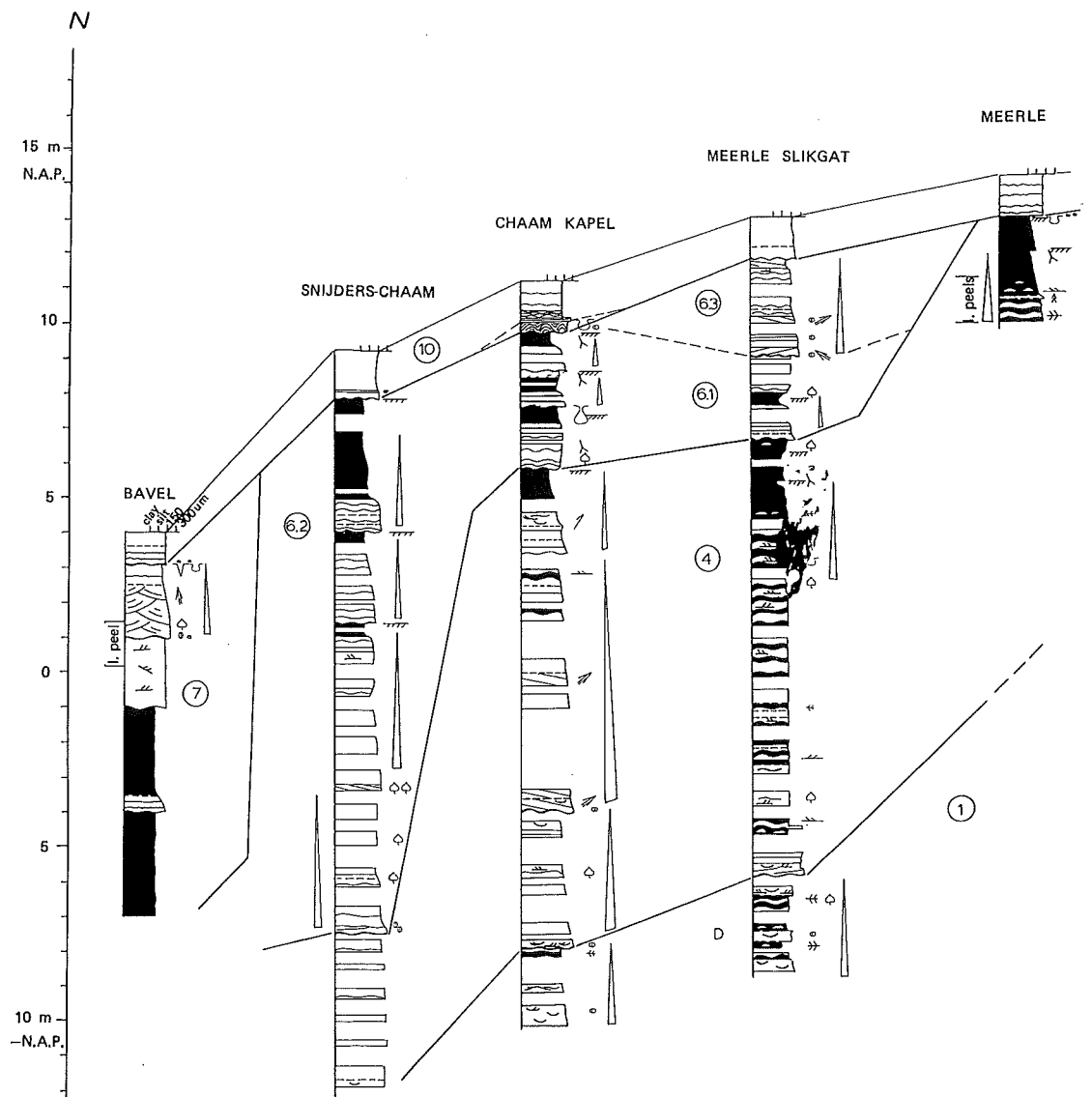
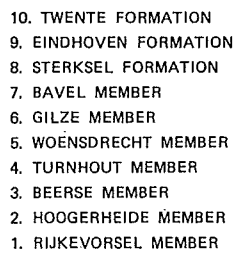


Fig. 3.3: Sedimentological cross-section between Beerse and Bavel, perpendicular to the depth contours of the North Sea basin.



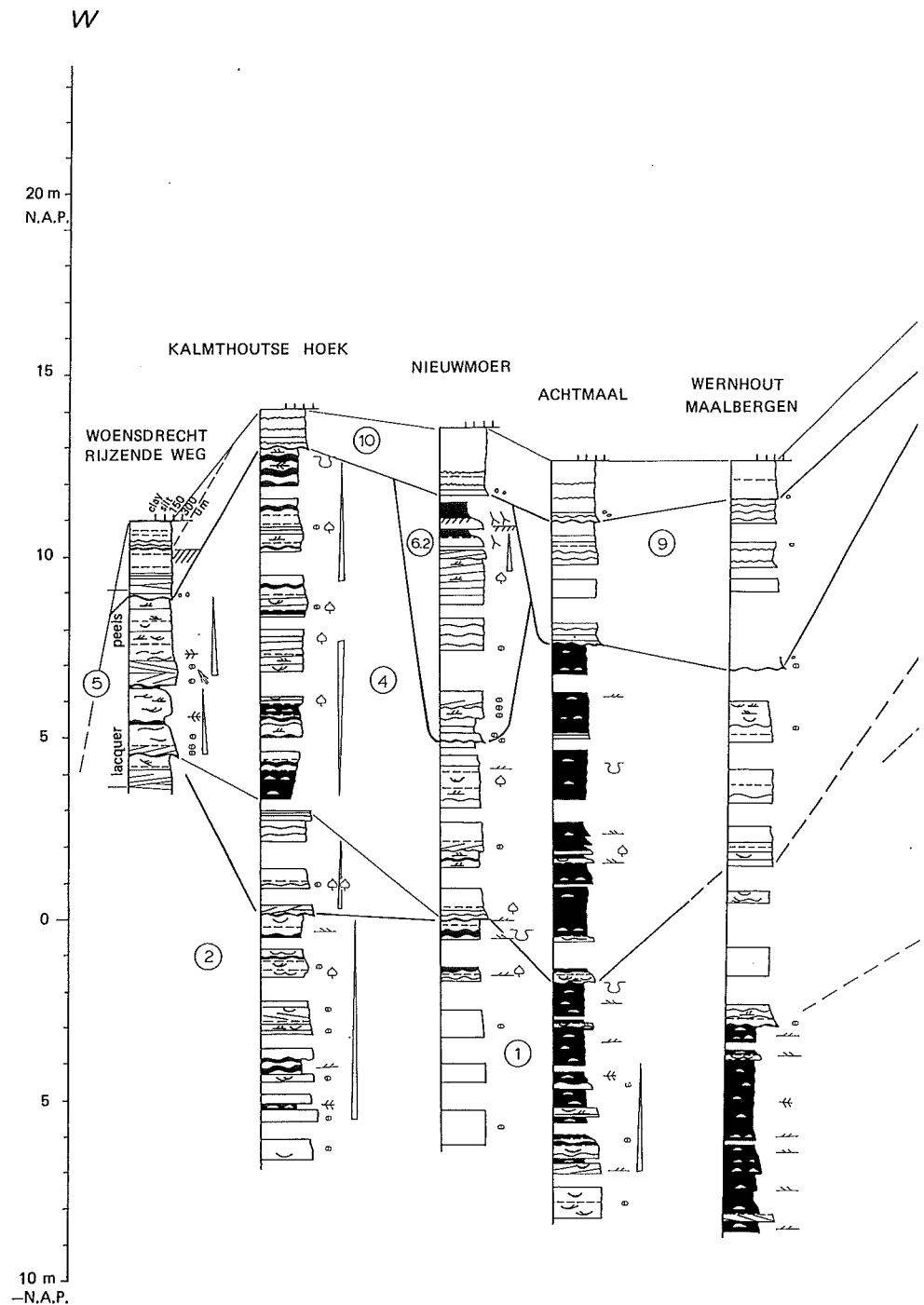
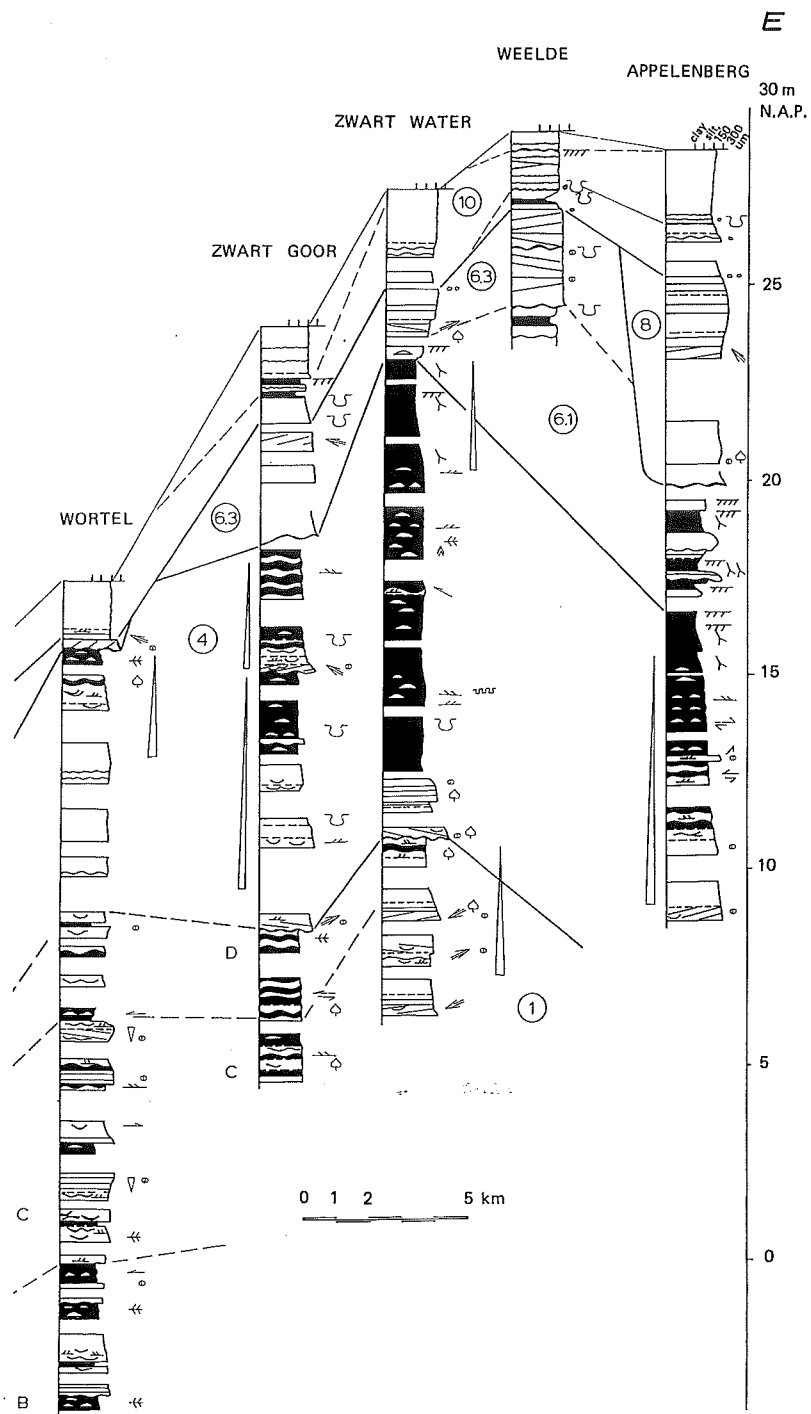


Fig. 3.4: Sedimentological cross-section between Woensdrecht and Appelenberg (Iage Mierde), parallel to the depth contours of the basin.



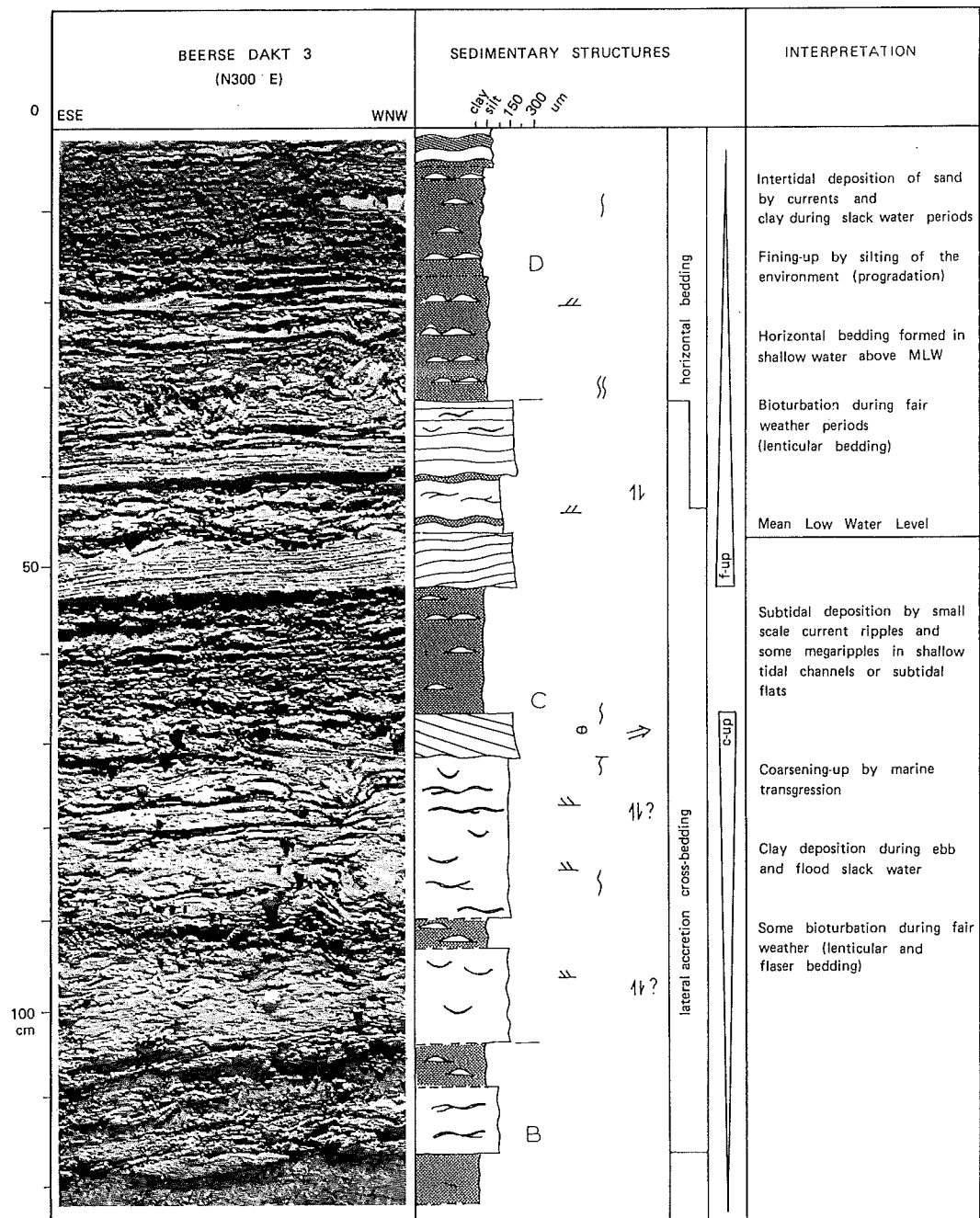


Fig. 3.5: Inshore tidal, landward facies of the Rijkvorsel Member at Beerse Dakt with weakly bioturbated, well developed lenticular and flaser bedding.

The largest sedimentological break occurs at the base of the low-angle, cross-bedded sand (fig. 3.5: at 70 cm). Large-scale cross-bedding in landward tidal environments is associated with megaripples below MLW (subtidal). Bidirectional ripples with mud-drapes (subtidal) were not found above the low-angle cross-bedding. The MLW level was probably not below the largest sedimentological break, as then the coarsening-up sequence (70-120 cm) would have been affected by erosion. A hypotheti-

cal MLW level just above the low-angle cross-bedding, is deduced from these facts.

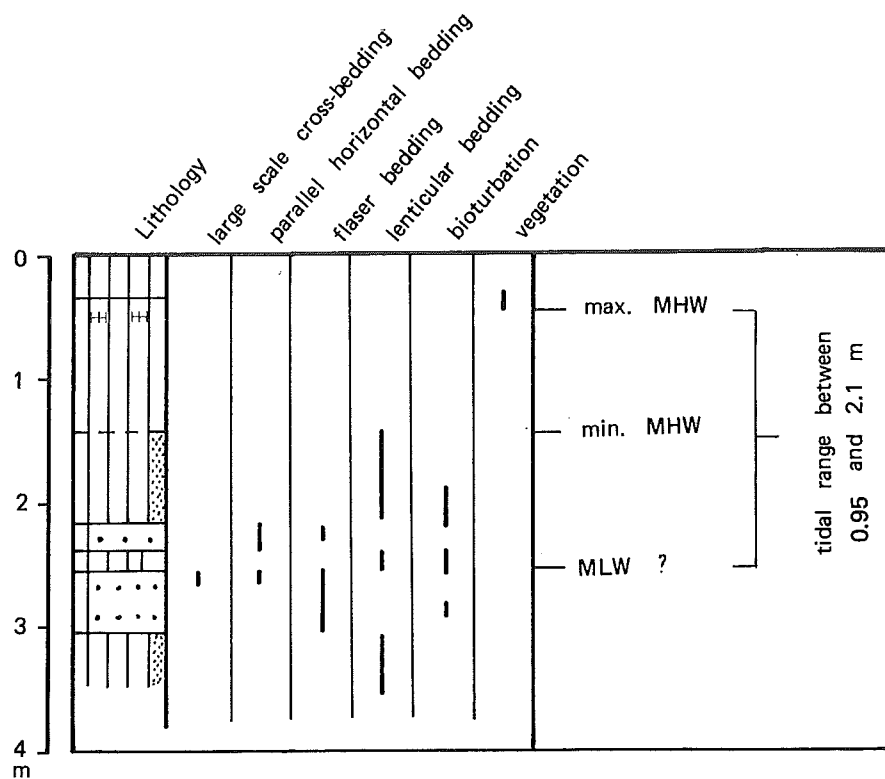


Fig. 3.6: Approximation of the tidal range during final silting of the Rijkevorsel Member at Beerse Dak.

The MHW level can be estimated more accurately. The lenticular bedding and bioturbation in the fining-up sequence, are of subtidal or intertidal origin, below the MHW level (min. MHW). Wavy, crinkly, salt-marsh sediment, of which the base is formed 10-20 cm below MHW (Roep and Van Regteren Altena, 1988) was not found here, because of the landward depositional environment. The in situ humic soil horizon probably developed above MHW (max. MHW). When the MHW and MLW levels have been established, the tidal range at Beerse Dak is valued between 0.95 and 2.1 m (fig. 3.6). This range is not corrected for later compaction, which according to Zonneveld (1960) can be as much as 50%.

As a conclusion, the tidal range estimation for the Rijkevorsel Member at Beerse Dak is not very reliable, because the mean low water level is uncertain. A more detailed discussion and a more reliable tidal range estimation is given for the Turnhout Member at Meerle (§3.3.4).

3.3.3 Beerse Member

Description of the sedimentary structures

The Beerse Member is restricted in its occurrence to the southeastern part of the investigated area (fig. 3.3). Two lithofacies are distinguished (§2.5.4).

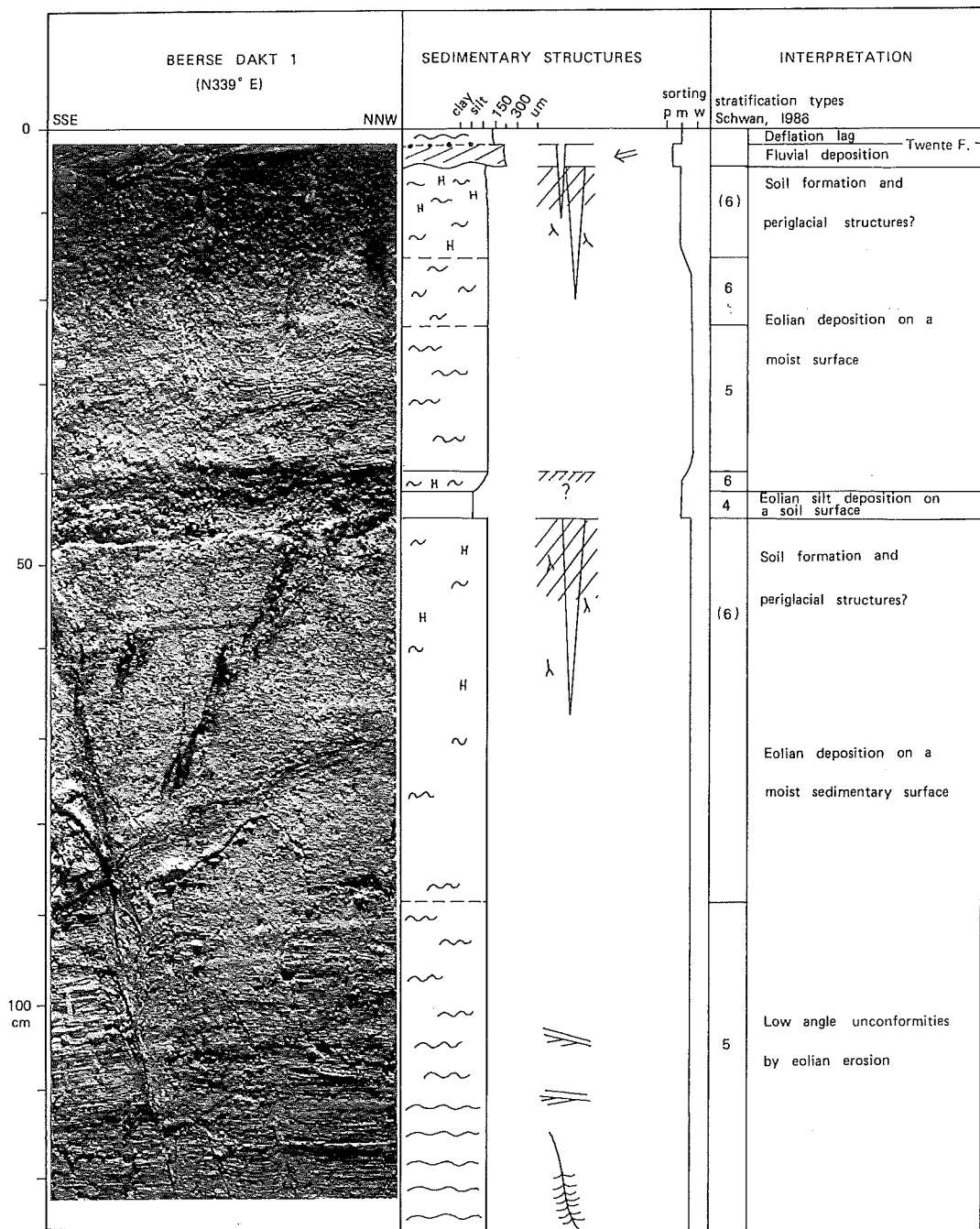


Fig. 3.7: Wet eolian deposition by adhesion ripples and two faint soil horizons in the upper part of the Beerse Member at Beerse Dakt.

Lithofacies 1 contains fine to medium sand with several humic or peaty soil horizons and periglacial structures (fig. 3.3: Beerse Dakt and Merksplas Strafinrichting). In Beerse Dakt (fig. 3.7, 3.8) the facies is characterized by continuous and discontinuous, crinkly bedding and four soil horizons. Massive bedding (on top of the paleosols), parallel horizontal bedding and small-scale cross-bedding occur infrequently. Deformations affect the lower paleosol (fig. 3.8). Frost cracks and

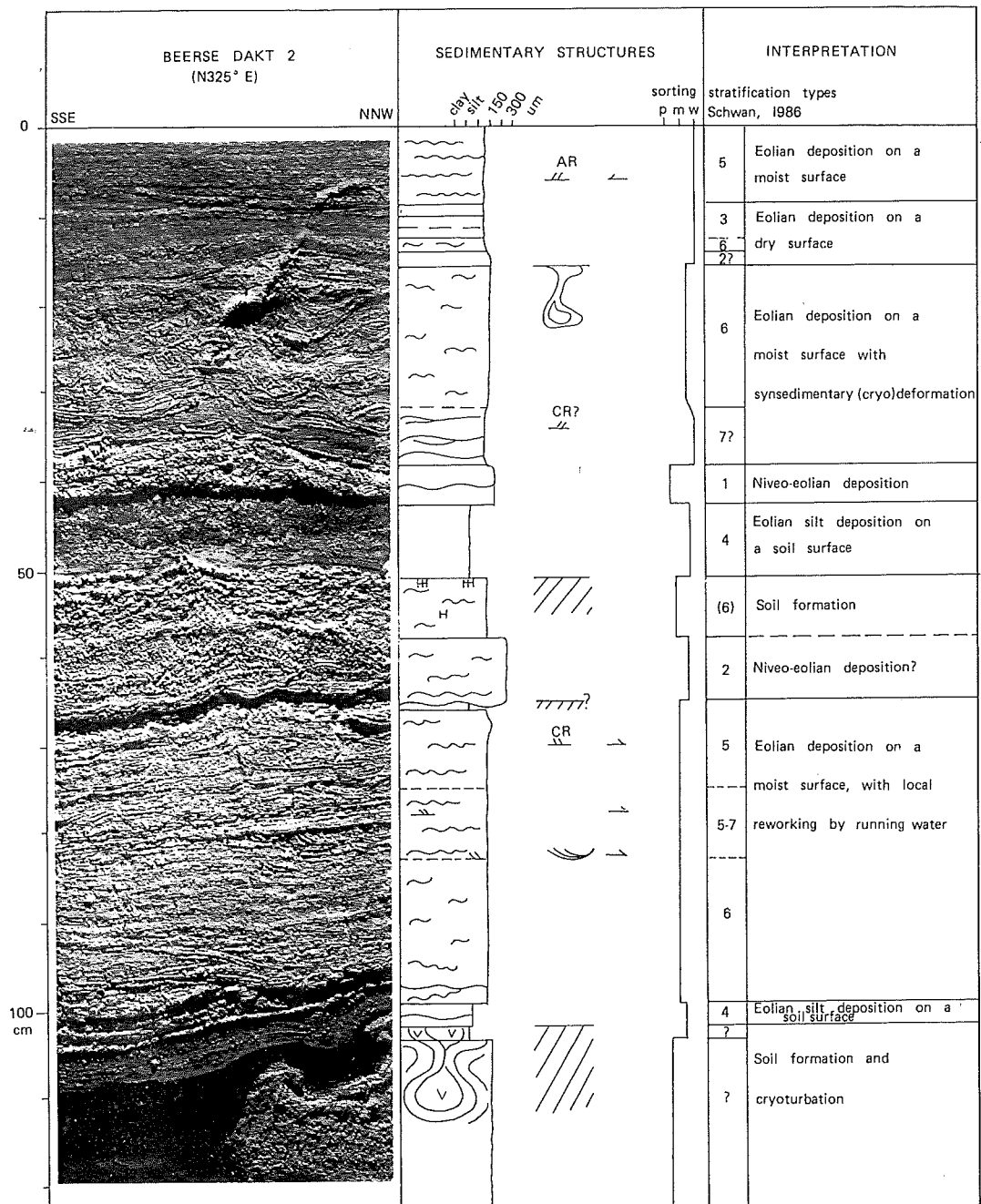


Fig. 3.8: Wet eolian deposition by adhesion ripples and local surficial runoff. The lower of the two soils has been cryoturbated. Lower part of the Beerse Member at Beerse Dakt.

small ice-wedge casts are present between the soils (see Appendix). In Merksplas Strafinrichting (fig. 3.9) lithofacies 1 shows a fining-upward sequence. Deformed, discontinuous, crinkly bedding changes upward into massive, wavy and parallel horizontal bedding, with coarse grained ripples (WR). Four paleosols are present in Merksplas Straf. (see App.), which are intensively deformed locally, with wave amplitudes up to 0.7 m. Lithofacies 2 (App. Beerse Dakt: bed 18) consists of medium to coarse sand with large-scale cross-bedding.

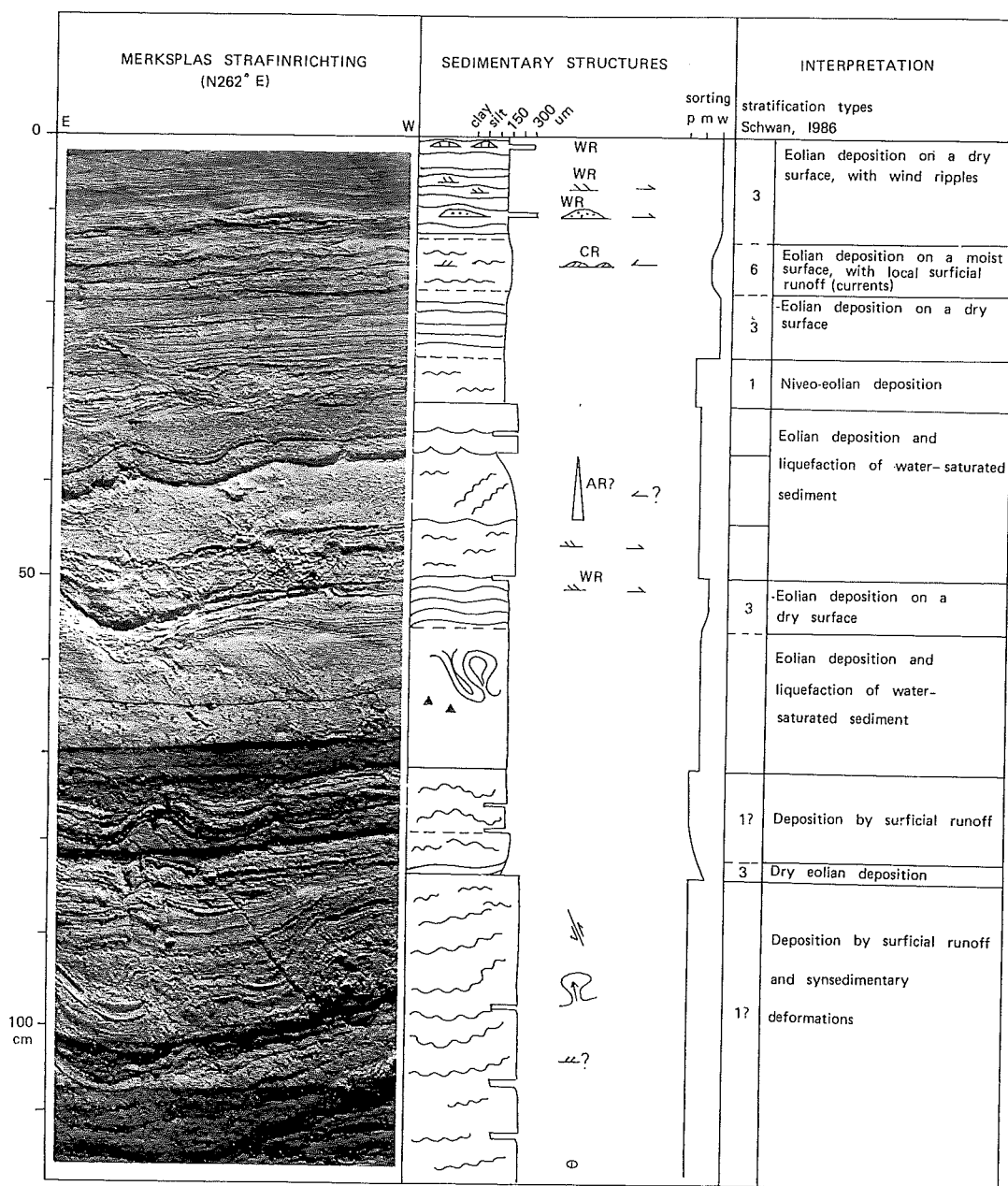


Fig. 3.9: Surficial runoff deposits changing upwards into dry eolian deposits with plane bedding. Beerse Member at Merksplas Strafinrichting.

Interpretation

The sedimentary structures in lithofacies 1 of the Beerse Member are interpreted in accordance with Schwan (1986). Several of his stratification types in Weichselian eolian coversands could also be distinguished in the Early-Pleistocene Beerse Member.

The discontinuous, crinkly bedding in Beerse Dakt (fig. 3.7, 3.8) is explained by the adhesion of windblown sand in plane beds or small adhesion ripples on a moist surface. Local reworking of these eolian

sediment by surficial runoff formed some small-scale current ripple cross-bedding (fig. 3.8 at ± 80 cm). The occurrence of parallel horizontal bedding at the top of fig. 3.8 points to eolian deposition in plane beds or by small wind ripples on a dry sedimentary surface. Periods of stagnation in the eolian sedimentation of sand are reflected by soil horizons and massive loam-beds (fig. 3.7, 3.8).

The fining-upward sequence at Merksplas Strafinrichting (fig. 3.9) reflects a synsedimentary decrease in moisture content and an increase of the eolian deposition. The deformed, discontinuous bedding in poorly to medium sorted sand is interpreted as a surficial runoff deposit. Deformations originated due to oversaturation of water in the pores between the sandgrains. Waterdepth must have been minimal, because intercalations of parallel horizontal bedding occur (interpreted as dry eolian deposits) in the surficial runoff sediments.

The massive beds in the middle of the peel (fig. 3.9) are explained by deposition of windblown sediment on a very wet surface. Periodic dryer conditions on the sedimentary surface are reflected by parallel horizontal bedding, which occur in between the liquefied beds. The parallel horizontal bedding was formed by eolian deposition of small wind ripples and plane beds on a dry surface. In the upper part of fig. 3.9 dry eolian, parallel horizontal bedding dominates. Coarse-grained (granule) wind ripples (WR) were locally preserved on the eolian surface.

The interpretations presented above confirm results of Haest (1985), who concluded to an eolian origin of the Beerse Member on granulometric grounds.

Geomorphological position

Geomorphological arguments support the eolian interpretation of the deposits. The stacked sand-units and paleosols, which are present in Merksplas Strafinrichting (App.), have all been formed in the same geomorphological situation. Humic, sandy soils are present on higher topographical positions in the eastern part of the exposure. Low lying, peaty soils occur in the west. The intervening sand-units occur as sand-sheets, with uniform thickness between the soils. Deposition by running water would have caused local erosion, flattening of the topography and infilling of low lying places. However, relief differences continued to exist during the successive sedimentation phases. Erosion hardly occurred in the receiving sites. This concordant upbuilding is explained by eolian deposition in sand-sheets (Ruegg, 1983; Schwan, 1986; Kocurek and Nielson, 1986).

Paleosols

The paleosols represent periods of non-sedimentation and surface stability, between the sand-sheet deposits. Peaty soils developed in low lying, wet places; humic, sandy soils formed on higher, dryer locations (App. Merksplas Straf.). The peaty wet soils were more subjected to cryoturbation than the dry soils, because of a higher soil moisture content.

The paleosols at Beerse Dakt (fig. 3.7, 3.8) are capped by a loam-layer. This loam is probably of eolian origin (no current ripples, no gullying). The deposition of eolian silt is explained by local surface stability (=soil formation), when sand transport was hampered by vegetation. Fall out of suspended silt formed a loam-layer on top of the soil horizon. Later the region was reached again by migrating sand-sheets and local sand transport dominated over the regional fall out of silt.

Periglacial phenomena

The Beerse Member is characterized by the presence of periglacial phenomena. Frost cracks, small ice-wedge casts (25 cm broad, 50 cm deep) and cryoturbations (50-70 cm amplitude) are present; associated with soil horizons and sand-units (fig. 3.7, 3.8, 3.9 and appendix). The periglacial phenomena allow an estimation of the mean annual temperature. The frost cracks, cryoturbations and small ice-wedge casts point to a cool to cold climate with (local) permafrost conditions and a mean annual temperature around -5 °C (Romanovskij, 1985).

The pollen spectra from the paleosols (see chapter 4) indicate a cool climate as well. Thermophilous trees are absent and contrary to the opinion expressed by Haest (1985) there is no reason to suppose warmer conditions during soil formation.

Lithofacies 2:

The large-scale cross-bedding and coarse sand with clay-pebbles and fine gravel, point to high stream velocities and megaripple migration. Lithofacies 2 is interpreted as a fluvial deposit.

3.3.4 Turnhout Member

The Turnhout Member is an important unit, which is present over the complete study area (fig. 3.3, 3.4). The member consists of fine to medium, micaceous sand and clay and is characterized by an unstable heavy mineral association (§2.5.5). Grain-size increases to the north and west, where the Turnhout Member is laterally connected to the Woensdrecht Member (fig. 3.3, 3.4). Vertical grain-size variations occur under the form of fining-upward sequences.

Description of the sedimentary structures (fig. 3.3, 3.4, 3.10, 3.11)

The base of the Turnhout Member was investigated at Beerse Blak (fig. 3.10; App.). Geys (1975, fig. 2.13.2) described a corresponding unit in a nearby pit, 5 to 8 m below the surface. Medium coarse sand with large-scale, tabular, unidirectional cross-bedding is laterally replaced, towards the NNW, by finer-grained sand with small-scale cross-bedding and possibly some herringbone cross-bedding. The cross-bedded sands are covered rather abruptly by clay.

Above the base of the Turnhout Member a sand- and clay-facies have been found. The sands are characterized by massive bedding, flaser bedding, wavy bedding and some large-scale cross-bedding (fig. 3.3 and 3.4). Fining-upward sequences are locally present in the sands (fig. 3.3: Chaam Kapel). The sands are laterally equivalent with thick clay/loam-beds, which are dominated by lenticular and wavy sand-clay bedding (fig. 3.3: Meerle Slikgat; fig. 3.4: Zwart Water, Achtmaal). Thick clay-beds are also found along the southern margins of the depositional environment (fig. 3.3: Merksplas Straf.; Appendix Beerse Blak). The massive or lenticular bedded clay at Merksplas Strafinrichting is found in gully structures eroded in the Beerse Member. Medium coarse sand and peat-lumps occur at the erosional contact.

A decrease in grain-size occurs towards the top of the member (fining-up sequence). Large-scale cross-bedding and flaser bedding give way to wavy sand-clay bedding, lenticular bedding and massive clay with peaty horizons (fig. 3.3: Merksplas Straf., Meerle, Meerle Slikgat; fig. 3.4: Appelenberg, Zwart Water). The top of the fining-upward sequence was studied in detail in Meerle (Kasse, 1986; fig. 3.3 and 3.11). Lenticu-

lar and flaser bedding with bidirectional, mud-draped cross-bedding are replaced upward by wave ripple cross-bedding (locally truncated) (fig. 3.11: + at 60 cm). Lateral accretion bedding is replaced by horizontal bedding at the same level. Wavy sand-clay bedding, parallel horizontal bedding, lenticular bedding with unidirectional small-scale cross-bedding and massive clay occur in the upper part of the sequence (fig. 3.11). A peat-layer is present at 45 cm above the lacquer peels (fig. 3.3).

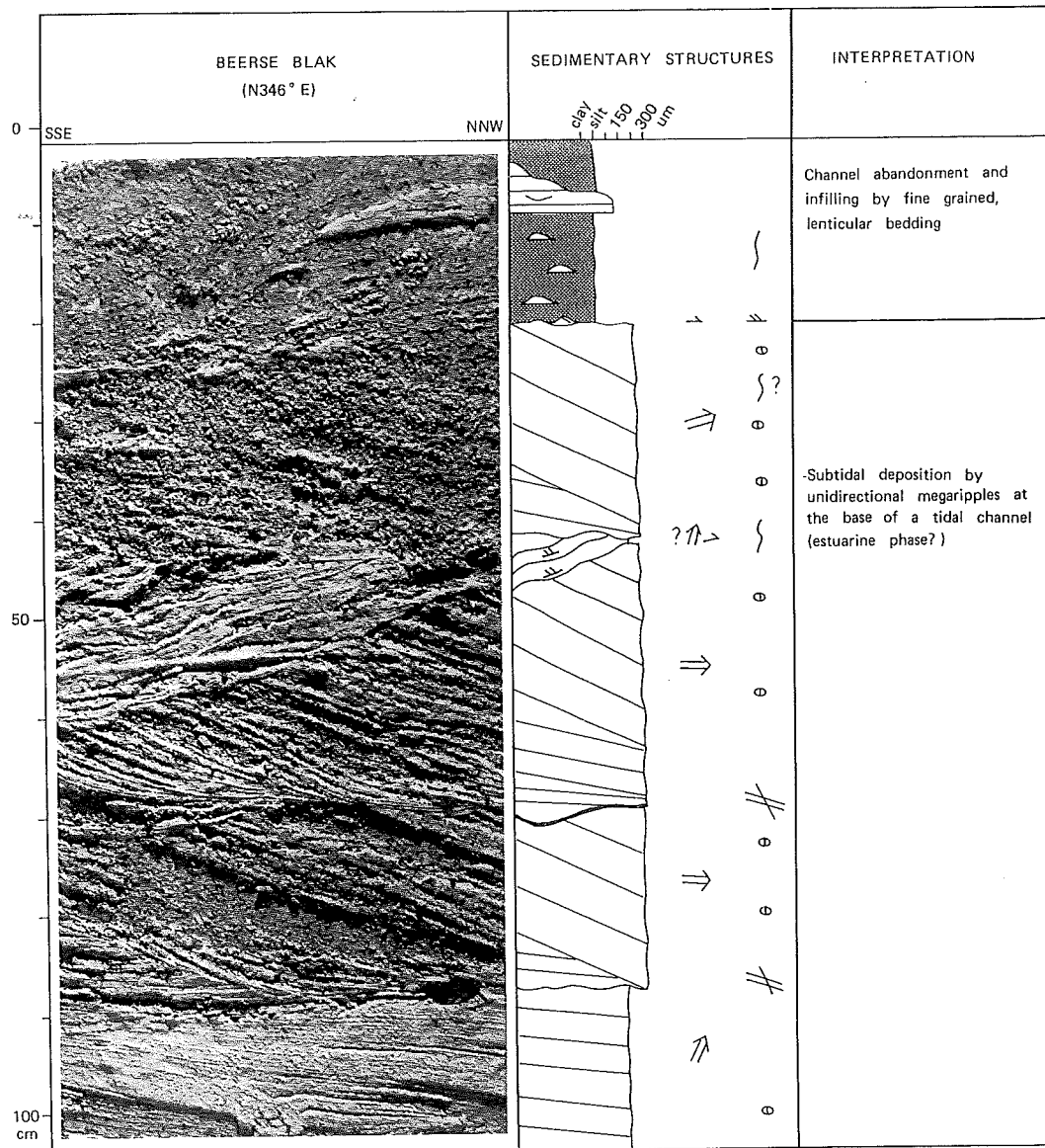


Fig. 3.10: (Sub)tidal channel-fill by unidirectional megaripples at the base of the Turnhout Member at Beerse Blak.

Interpretation

The lack of molluscs and diatoms hampers the environmental interpretation. The regular alternations of sand and clay-laminae, especially in the fining-up sequence at the top of the member, and the high-angle,

opposed cross-bedding (fig. 3.3, 3.4, 3.11) are explained by tidal, ebb and flood sand transport and slack-water clay deposition (Kasse, 1986).

The medium coarse, large-scale cross-bedded sand with many clay-pebbles at the base of the Turnhout Member in Beerse Blak and Meerle Slikgat (fig. 3.3: 18-19 m) is interpreted as a megaripple deposit on the bottom of a tidal channel. It reflects an erosional phase, in which the underlying Beerse Member was partly (fig. 3.3: Merksplas Straf.) or completely eroded (fig. 3.3: Meerle Slikgat; App.: Beerse Blak). North-northwest flowing currents were dominant in Beerse Blak (fig. 3.10). Because of this erosion, the Turnhout Member only consists of a regressive, progradational, tidal sequence. A transgressive, vertical sequence (e.g. substratum, peat, fresh water lagoonal clay, salt water tidal deposits; Reineck, 1970) has not been found.

After this erosional phase the depositional environment changed rather abruptly. The tidal channels at Beerse Blak and Meerle Slikgat were abandoned and silted up with clay (fig. 3.3, 3.10). The environment became more quiet and sheltered (perhaps locally lagoonal). A progradational tidal sequence was formed (fining-upward) by seaward migration of the tidal environments (tidal channel sand, tidal flat sand and clay, marsh/peat) (fig. 3.3: Chaam Kapel, Meerle Slikgat; fig. 3.4: Appelenberg, Zwart Water). The flaser bedded, massive and large-scale cross-bedded sands in the lower part of the Turnhout Member were probably formed in tidal channels (fig. 3.3, 3.4). Stacking of channel sequences was found infrequently (fig. 3.3: Chaam Kapel; fig. 3.4: Zwart Goor). Only subtidal (and intertidal?) channel deposits, which have a higher preservation potential than supratidal deposits, have been found. Grain-size in the channels increases towards the north and west, which points to more turbulent tidal conditions with higher current velocities (fig. 3.3: Chaam Kapel, Snijders-Chaam) (Van Straaten, 1964). Beyond the tidal channels, thick (10 m) loam and clay-beds without major sedimentological breaks could develop in quiet conditions (fig. 3.3, 3.4: Meerle Slikgat, Zwart Water, Achttmaal). Deposition occurred predominantly in a subtidal setting, since ebb and flood sand ripples are both covered by slack-water mud. Supratidal deposits (marsh sediments, peat) were not formed in these loamy/clayey interchannel environments. The fine-grained interchannel areas point to little tidal channel migration. This channel stability is an indication for the landward (distal) setting of the tidal environment with respect to the sea.

At the southern margins of the depositional environment thick clay-beds were formed during the deposition of the channel sands and interchannel fines further north (fig. 3.3: Merksplas Straf.; App.: Beerse Blak). Part of these marginal clays are probably of supratidal origin: the absence of pollen in certain levels points to synsedimentary exposure and oxidation. The high amount of Chenopodiaceae pollen in this border zone (App.: Merksplas Straf., Beerse Blak, Ravels) is explained by local Chenopodiaceae stands in a (supra)tidal litter zone (§3.4).

The fining-upward sequence towards the top of the Turnhout Member reflects the final stages of deposition in the tidal environment. Current velocities decreased and flaser bedding was succeeded by wavy and lenticular bedding.

Tidal range at Meerle

The regular fining-upward sequence at Meerle, capped by a peat-layer, (fig. 3.11) is an indication for silting at a constant sea-level. In comparison to tidal range estimations for other members, the estimation

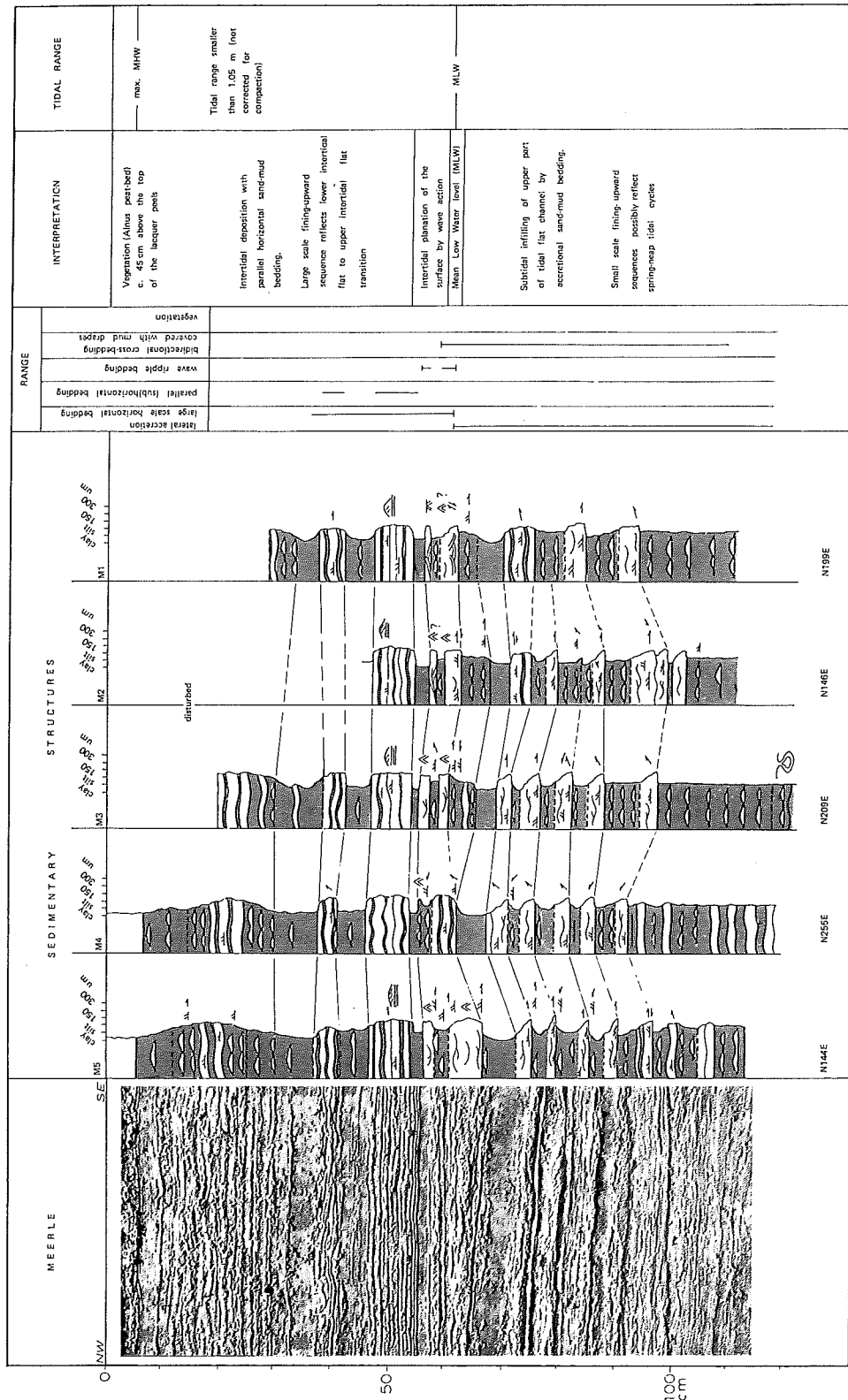


Fig. 3.11: Inshore tidal, landward facies of the Turnhout Member at Meerle. Well developed fining-upward sequence around the mean low water level and estimated tidal range.

presented here is more reliable, since mean low water (MLW) and mean high water (MHW) level could be fixed rather accurately by the range of certain sedimentary structures.

The large-scale, low-angle bedding in the lower part of the peels (fig. 3.11: 60-120 cm) is interpreted as a subtidal (mud-draped ebb and flood ripples) lateral accretion deposit. Current directions to the south are strongly dominant. The dominant southsoutheast current direction in the fining-up sequence, most likely represents the flood current.

The change from subtidal pointbar cross-bedding, into horizontal unidirectional cross-bedding with wave ripples, is interpreted as approximately the MLW level (fig. 3.11: at 60 cm). Wave action indicated by wave ripples, is most effective on the intertidal flats and tends to flatten depositional surfaces (Van Straaten, 1964). Above MLW silting continued by (unidirectional) flood currents, forming wavy bedded and lenticular bedded units. Current velocity sometimes dropped below the minimum velocity for current ripple formation and parallel horizontal sands were deposited during flood (Roep and Van Regteren Altena, 1988). Thickening up and thinning up of the parallel horizontal sets was perhaps caused by neap - spring - neap tide cycles. During spring tides flood current velocity exceeded the threshold stream velocity required for current ripple formation and current ripples developed on top of the parallel horizontal beds (fig. 3.11 at 50 cm).

In the final stages of silting, crumbly clay was deposited, capped by a peat-layer (fig. 3.3: Meerle, Meerle Slikgat; fig. 3.4: Appelenberg, Ravels, Zwart Water). The crumbliness of the clay and local absence of pollen (Meerle, Merksplas Straf.), is attributed to periodic intertidal or supratidal exposure. The fining-up sequence (from intertidal to supratidal deposits) is very gradual, which points to a landward tidal setting, for instance comparable to the recent Dollard basin in the northeastern Netherlands (Bakker, 1974). Salt-marsh sediments with crinkly, parallel bedding, of which the base is formed at 10-20 cm below the mean high water level (Roep and Van Regteren Altena, 1988), are not present.

The peat-bed at Meerle lies in situ on top of the clay (App. Meerle). The peat is dominated by *Alnus* pollen and must therefore have been formed above local mean high water (max. MHW). When both MLW and MHW levels are established, tidal range can be estimated at 1.05 m (fig. 3.11). If a 50% compaction rate is accepted (Zonneveld, 1960: Holocene, tidal fresh water deposits in the Biesbos area) for Early-Pleistocene deposits, then tidal range amounted to approximately 2 m. However, it is stressed that:

- this estimated tidal range is only valid for location Meerle.
- the compaction rate is not exactly known.
- increase and decrease of the tidal amplitude due to estuarine effects are unknown.
- a different tidal range may have occurred in earlier phases of deposition of the Turnhout Member.

Siderite concretions

Siderite nodules were found locally in a horizontal bed, 0.5 m below a peat-layer at Ravels. According to Wilson (1965) these nodules are commonly associated with fine, gray members; in particular below coal seams. He interpreted the nodules as precipitations from slightly reducing groundwater in a permanently saturated soil. The nodules in Ravels are still white and not oxidized. This indicates permanent reduction of the Turnhout Member after deposition. Nowadays, the tidal deposits are non-calcareous. The intertidal and supratidal sediments of

the Turnhout Member could have been decalcified during the silting process (Van der Sluys, 1970). Subtidal deposits, however, are primary always calcareous (Van Straaten, 1964). The subtidal deposits of the Turnhout Member must, therefore, have been decalcified after deposition. As the siderite concretions are still unoxidized, it is concluded that the decalcification of the subtidal deposits occurred by post-depositional groundwater flow under reducing conditions.

Paleosalinity

Bioturbation is normally important in salt-water environments such as the intertidal flats of the recent Dutch Waddenzee (Van Straaten, 1964). The scarcity of bioturbations in the Turnhout Member is an indication for a low paleosalinity and a fresh or brackish water tidal environment. However, unlike the subrecent fresh water tidal environment of the Biesbos area southeast of Rotterdam (Zonneveld, 1960), the depositional environment was not completely fresh. Concentrations of pyrite and high percentages of Chenopodiaceae pollen occur locally in the top of the Turnhout Member (App. Ravels) (Dricot, 1961). Oxidation of the pyrite in the clay in clay-pit Ravels resulted in yellowish jarosite precipitation on exposed surfaces. Pyrite formation requires sulphate from seawater and a reducing environment. Therefore, regular influxes of salt or brackish water must have occurred in the depositional environment of the Turnhout Member.

The presence of peat with a high *Alnus* pollen content at the top of the member points to a temporarily sharp salinity decrease. The vegetation required regular flooding by fresh, eutrophic river water. Otherwise the peat would have developed into a more oligotrophic type (Roeleveld, 1974). These fresh water peats were later drowned by the sea and brackish water clay was again deposited (pyrite, Chenopodiaceae pollen) (App. Ravels, Beerse Blak).

Conclusion

The Turnhout Member was formed in an inshore, landward, fresh to brackish, micro- to mesotidal environment. Several depositional sub-environments are described: tidal channels, clayey interchannel areas, intertidal mixed flats and mudflats, tidal litter zones and fresh water swamp.

3.3.5 Hoogerheide Member

The Hoogerheide Member consists of fine to medium coarse sands with locally a clay-layer at the top. This member is in general more sandy than the laterally related Rijkevorsel Member, which contains more clay-lenses within the member (§2.5.6).

Description of the sedimentary structures (fig. 3.12, 3.13, 3.14)

The 7 m thick fining-upward sequence at Kalmthoutse Hoek is characterized at the base by large-scale, low-angle cross-bedding in medium coarse sand (fig. 3.12). The upper part is finer grained with wavy and flaser bedding and some bioturbation. Above this fining-upward sequence a 3 m thick sand-bed (11-14 m below the surface) is present dominated by low-angle cross-bedding, wavy parallel and parallel horizontal bedding. No sharp bounded clay-laminae or opposed, small-scale cross-bedding have been found. The stratigraphical position is uncertain.

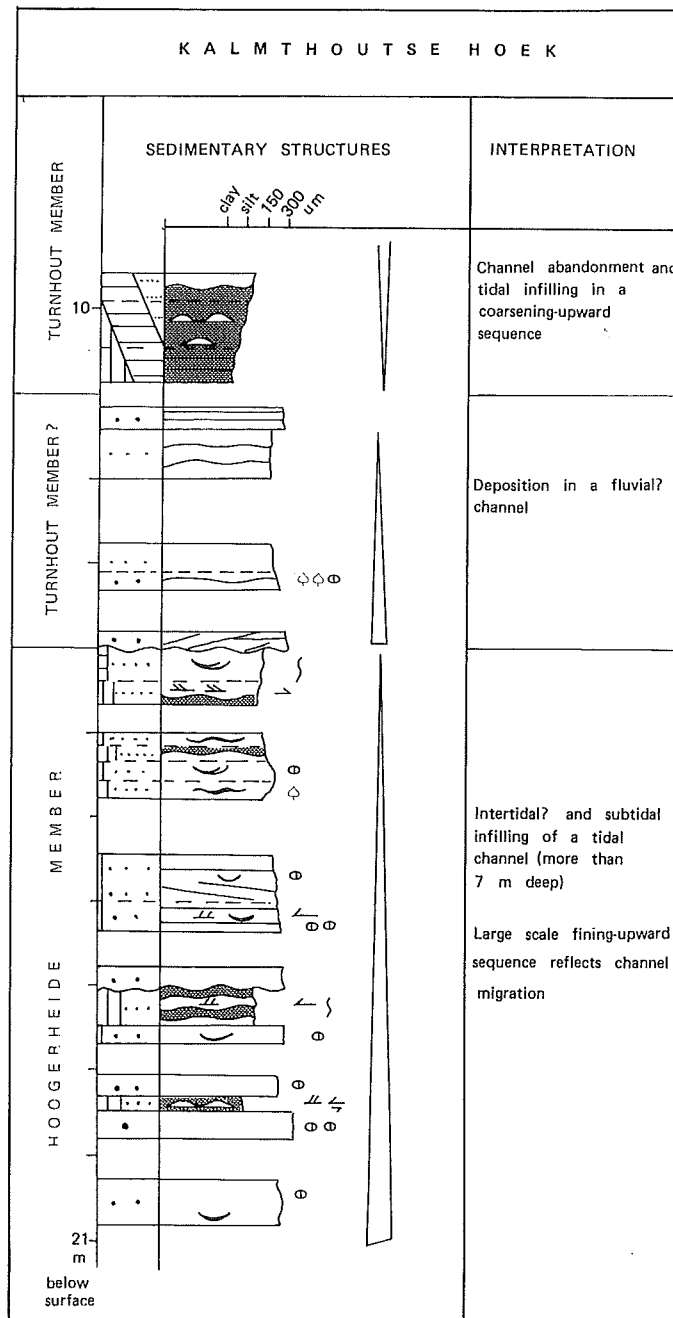


Fig. 3.12: Fining-upward sequence in a coarse-grained tidal channel-fill of the Hoogerheide Member at Kalmthoutse Hoek.

The upper part of the Hoogerheide Member was studied in several sand-pits west and south of Hoogerheide. The flaser bedding and herringbone cross-bedding at Woensdrecht Hooghuis (WH) (fig. 3.13) are the most characteristic structures in the very well-sorted sands. Towards the top a faint decrease of mud-flasers occurs (coarsening-upwards). Bidirectional, mud-draped current ripple cross-bedding in the lower part of the peel is succeeded by flaser bedding and small-scale cross-bedding. Climbing ripple bedding in drift (Reineck and Singh, 1980) grades into small-scale, tabular cross-bedding and parallel horizontal bedding.

Two types of bioturbation were found in Woensdrecht Hooghuis: Type 1 consists of round, 1 cm wide tubes with a concentric, layered sand-mud filling. Type 2 are very small (1 mm wide or less), elongate tubes, filled with mud. The bioturbation is present in small-scale current ripple bedding with ripple height of 1 cm formed by more or less unidirectional currents to the northwest. Non-bioturbated current ripple beds have larger ripple height (1-4 cm) and are formed by more bidirectional currents to the northwest and southeast; in the top of the lacquer peels the current direction is dominant to the east.

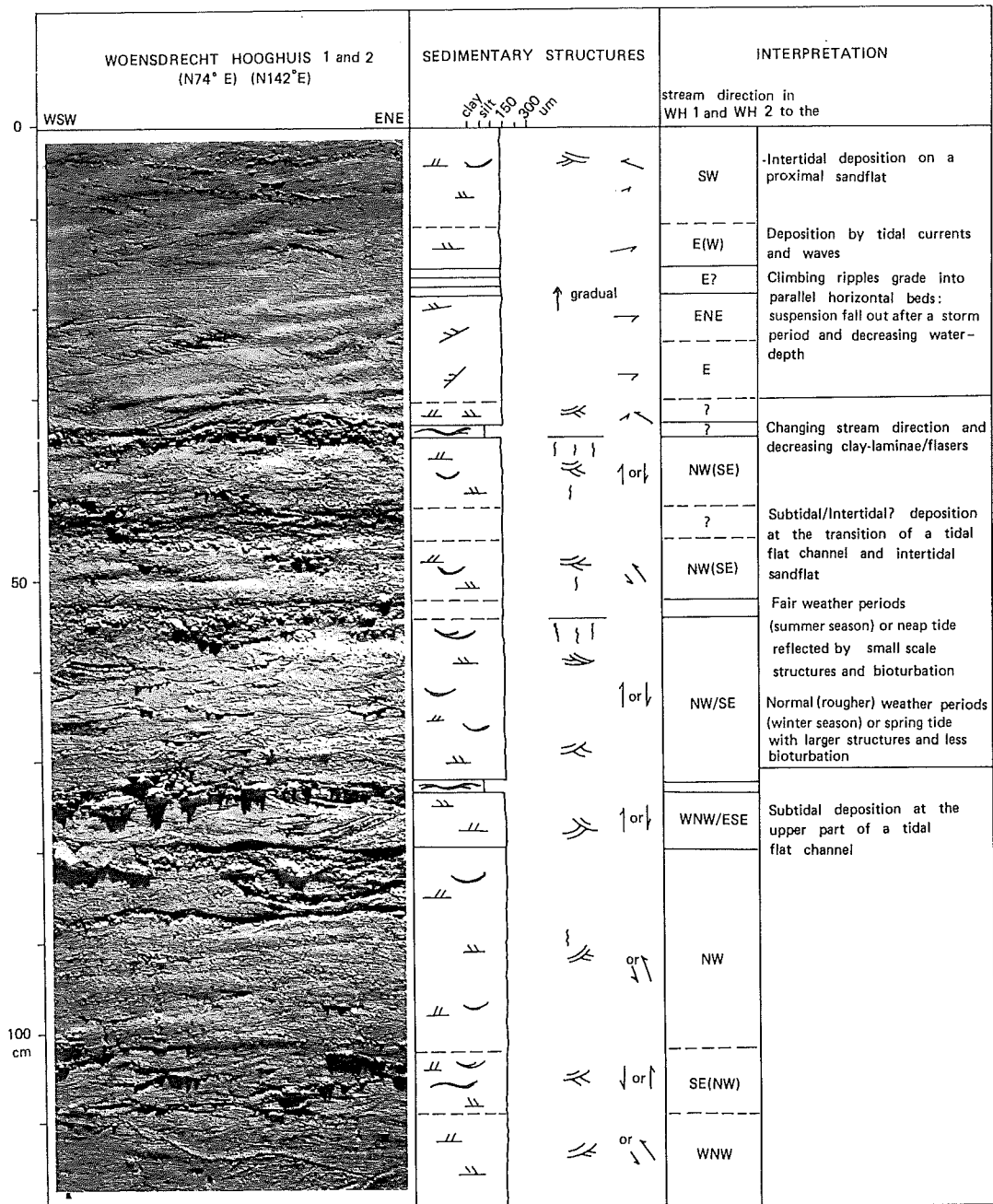


Fig. 3.13: Inshore subtidal and intertidal sandflat deposits characterized by flaser bedding and weakly bioturbated intervals. Hoogerheide Member at Woensdrecht Hooghuis.

The Hoogerheide Member in exposure Woensdrecht Rijzende Weg (WR) (fig. 3.14) is subdivided into four sub-units:

Unit 1 and 3 are dominated by small-scale, trough cross-bedding.

Unit 2 is formed by distinct sets with an undulating, erosional base. Each set consists of weakly developed relatively coarser grained large-scale, (low-angle) cross-bedded sand, which changes upward into finer grained horizontal and parallel bedded sand with an opposed dip.

Unit 4 is separated from unit 3 by a gradual boundary and it is dominated by climbing ripple cross-bedding. The angle of climb is variable (climbing ripple bedding in drift, type 1 and type 2: Reineck and Singh, 1980).

Interpretation

Kalmthoutse Hoek (fig. 3.12):

The regular occurrence of mud-laminae, the clay-pebbles and some bidirectional cross-bedding point to a tidal setting. The medium coarse, moderately sorted, large-scale cross-bedded sands with clay-pebbles are interpreted as megaripple deposits in a subtidal channel (Reineck and Singh, 1980; Van Straaten, 1964). Shells can be absent due to post-depositional decalcification. Lenticular and wavy sand-mud beds were formed on the channel bottom by sudden changes in hydrological conditions in the channel (Van Straaten, 1964).

The fining-upward sequence (7 m) is explained by the lateral migration of a more than 7 m deep channel. Silting of the channel is visualized by a change from large-scale cross-bedding into small-scale flaser and wavy sand-clay bedding. The bioturbation in the upper part of the channel-fill indicates a decrease in turbulence and subtidal or intertidal sedimentation.

Woensdrecht Hooghuis (fig. 3.13):

The mud-flasers and bidirectional herringbone cross-bedding illustrate the tidal character of the Hoogerheide Member. Bidirectional mud-draped ebb and flood current ripples point to subtidal sedimentation in the lower part of fig. 3.13. Northwestern directed ebb currents (see paleogeography) are slightly dominant.

The transition from climbing ripple bedding into current ripple bedding and parallel horizontal bedding (in sand of equal grain-size) indicates a shallowing of the water depth (fig. 3.13, top). The parallel horizontal bedding is interpreted as upper flow regime deposition on a nearly exposed intertidal sandflat. Although climbing ripple bedding is rare on tidal flats, it is locally abundant at the tidal flat - channel transition, when sand falls out from suspension after a storm period (Wunderlich, 1969). The slight decrease in mud-flasers towards the top of fig. 3.13 may point to the influence of wave action on the sandflat. According to Van Straaten (1964) wave action tends to flatten intertidal surfaces and to rework (remove) clay/silt from the intertidal sandflats. These considerations are in favor of a mean low water level in the middle of the lacquer peel (fig. 3.13).

The bioturbation types 1 and 2 in Woensdrecht Hooghuis resemble the burrows of *Nereis* (Reineck and Singh, 1980) and *Heteromastus* (Van Straaten, 1964). The bioturbated levels are related to smaller sedimentary structures; the non-bioturbated units to larger structures. These differences may be caused by seasonal or lunar variations in stream velocity (Reineck and Singh, 1980; Van den Berg, 1986). During fair weather (summer) or neap tide, tidal currents were weaker and sedimentary structures were smaller. As the sedimentation rate was relatively

low, burrowing animals partly destroyed the fair weather structures. In winter time or during spring tide, the current velocities were larger and sedimentation was more rapid. Ebb and flood water produced herring-bone cross-bedding. The animals were buried or moved to higher levels rapidly and hardly destroyed the sedimentary structures.

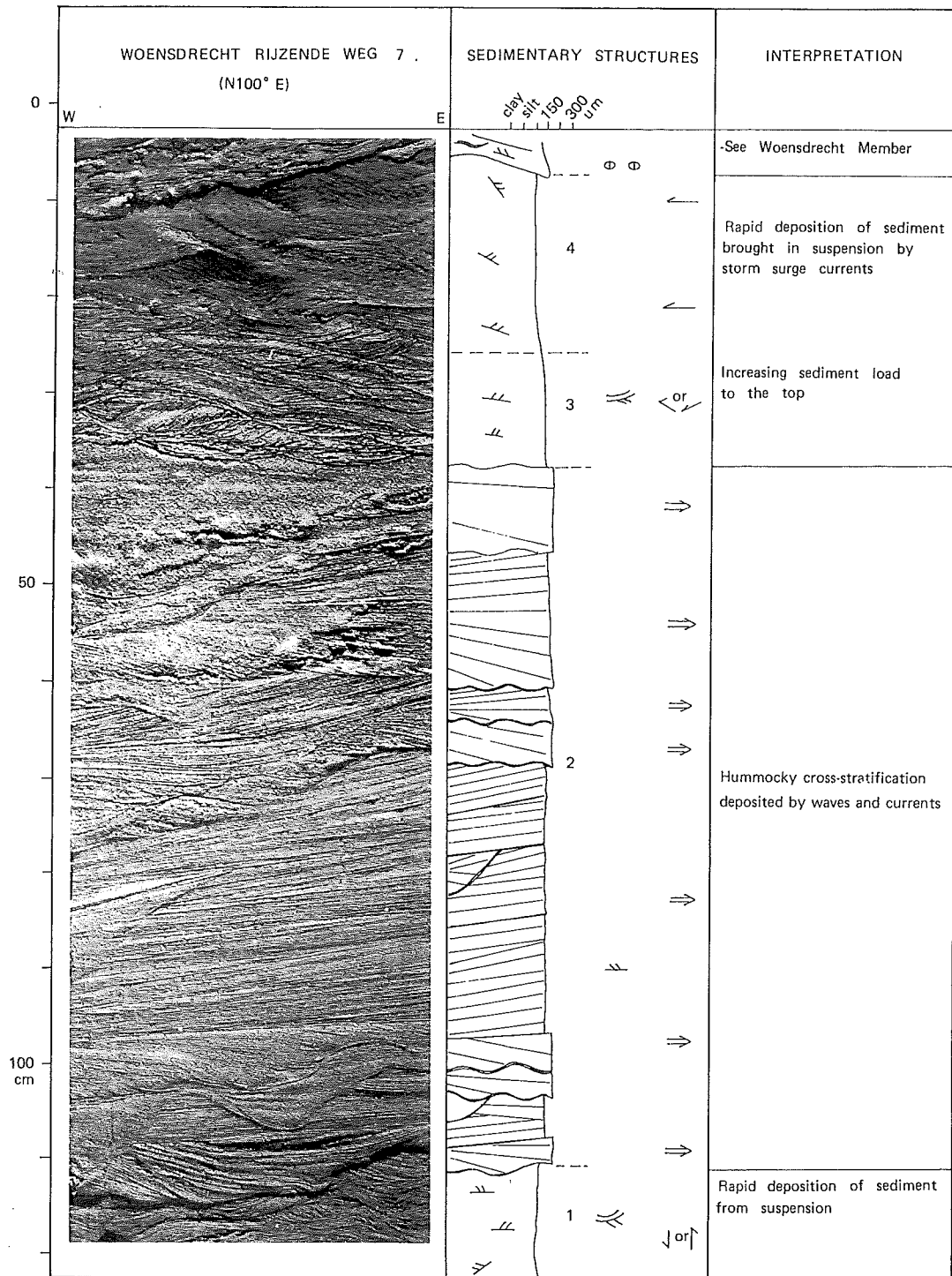


Fig. 3.14: Wave generated, low-angle (hummocky) cross-bedding and climbing ripple bedding. Hoogerheide Member at Woensdrecht Rijzende Weg.

Woensdrecht Rijzende Weg (fig. 3.14):

In this exposure there are no diagnostic indications of a tidal origin for the Hoogerheide Member. A tidal setting is proposed, however, because of the short distance between Woensdrecht Rijzende Weg and Woensdrecht Hooghuis.

Unit 4 was deposited in the form of climbing ripples in a short period of time by a westerly directed current. The trough cross-bedded units 1 and 3 are thought to have been formed by current ripples as well, at more or less right angles to the peel, because of the transitional boundary between unit 3 and 4 (environmental uniformity). Some of the sedimentary structures, however, can also be explained by wave action (offshooting and draping foreset laminae, bundled upbuilding and undulating lower set boundary (Reading, 1980).

Unit 2 is difficult to interpret. The individuality of the sets, the irregular base of the sets and the gradual change of large-scale cross-bedding into parallel bedding in one set, are not common in current dominated systems. The sedimentary structures in unit 2 show some resemblance to hummocky cross-stratification formed by the combined action of waves and currents in the nearshore surfzone of the Canadian Great Lakes (1.4-1.8 m water depth) (Greenwood and Sherman, 1986). Their hummocky cross-stratification is, however, more regular and wavy and does not possess a steep, irregular scoured base with low-angle cross-bedding as in unit 2.

Woensdrecht Rijzende Weg was probably situated at the border of an intertidal flat area. During storms the top of the intertidal flat was eroded and hummocky cross-bedding developed at the seaward side of the flats. Westward flowing ebb surge currents produced thick units of climbing ripple bedding (fig. 3.14). The hummocky cross-bedding suggests a nearshore setting for the Hoogerheide Member, but barrier island sediments have not been found so far.

Conclusion:

The sedimentary structures at Kalmthoutse Hoek and Woensdrecht suggest a proximal (=seaward), inshore, tidal depositional environment (Van Straaten, 1964). The environment is characterized by tidal channels (fig. 3.12: Kalmthoutse Hoek) and tidal sandflats. A MLW level could be established at Woensdrecht Hooghuis (fig. 3.13), but a MHW level is unknown. The proximity of the Hoogerheide Member with respect to the Rijkvorsel Member is indicated by:

- the relatively coarser-grained sediment
- the absence of intraformational clay-layers
- the presence of wave formed hummocky cross-bedding in the Hoogerheide Member.

3.3.6 Woensdrecht Member

This member consists of fine to coarse sands with a mixed heavy mineral association (§2.5.7). A continuous clay-layer at the top connects the Woensdrecht Member in the west with the Turnhout Member in the east. The former member is coarser-grained and no thick clay-layers occur within the member (fig. 2.3, 2.6).

Foraminifer *Ammonia beccarii*

Usually molluscs, foraminifers and diatoms are a common constituent in tidal deposits. In the Early-Pleistocene tidal units of Noord-Brabant, however, molluscs and diatoms are absent, possibly because of a low

salinity during deposition or due to post-depositional leaching. The calcareous tests of foraminifers were also never found, but in several samples the chitinous inner part of the foraminifers was preserved. In a total of 42 samples, prepared for the analysis of botanical macro remains, 9 samples contained 21 specimens all belonging to *Ammonia beccarii* (§3.4) (Huyzer and Van Toor, unpubl., bijlage 4). All the samples were taken from the clayey top of the Woensdrecht Member. Since other foraminifer species were not found it is assumed that *Ammonia beccarii* is present in situ. Reworking of forams from older (e.g. Tertiary) deposits would result in a mixed assemblage. According to Van Voorthuysen (1951) and Larssonneur (1975) *Ammonia beccarii* is found in marine, subtidal and intertidal flat environments. This ecological setting is in agreement with the results obtained from the sedimentary structures, from which a seaward, inshore (estuarine), tidal environment is proposed (see below).

Description of the sedimentary structures (fig. 3.15, 3.16, 3.17, 3.18, 3.19, 3.20, 3.21)

Woensdrecht Rijzende Weg (WR)(fig. 3.15, 3.16):

The section is divided into two sequences by two major sedimentological breaks (fig. 3.16: base WR 4; middle WR 3).

The lower sequence is characterized by large-scale, cross-bedded sands with many clay-pebbles at the base (fig. 3.16: WR 4), wavy flaser bedding, wavy sand-mud bedding (WR 4), small-scale trough cross-bedding with flasers and some lenticular bedding (WR 3).

The upper sequence starts somewhat above the middle of WR 3 (fig. 3.16). Large-scale cross-bedding with many clay-pebbles (WR 3) is covered by small-scale, trough cross-bedded sand with wavy, bifurcated and simple flasers and some parallel horizontal bedding (fig. 3.15: WR2; fig. 3.16: WR 1 and 2). The upper sequence has an upward decrease in grain-size and clay-flaser content (=decreasing heterolithicity). The sequences are summarized in fig. 3.16.

Bioturbation is restricted to one large burrow approximately at a level comparable to the base of WR 1.

Woensdrecht Hooghuis (fig. 3.17):

The major break at the base of fig. 3.17 reflects the erosive boundary of the Woensdrecht Member with the Hoogerheide Member. Large, curved bioturbation structures are present in the erosive base of the Woensdrecht Member. Large-scale, low-angle, accretional cross-bedding of sand and mud is the dominant bedding type. Clay-beds consist of clay-pebbles and in situ clay. The sand-beds reveal indistinct horizontal and small-scale cross-bedding.

The complete channel sequence in Woensdrecht Hooghuis is fining-upward with thinning-up of the sets, although some large-scale discordancies are present (see Appendix). The central part of the infilling seems to be more clayey than the slopes. The top of the sequence is horizontally bedded with thick, alternating beds of sand and clay. Sedimentary structures are locally destroyed by intense bioturbation.

Ossendrecht(OSD) (fig. 3.18, 3.19, 3.20):

Section Ossendrecht reveals 3 major breaks (middle of OSD 5, OSD 2 and OSD 1) separating 4 units (fig. 3.20):

Unit 1 is dominated by bidirectional cross-bedding with some continuous mud-laminae. Current direction is dominant to the west. Herringbone cross-bedding and climbing ripple bedding occur infrequently.

Unit 2 (fig. 3.18, 3.20) is characterized by large-scale, tabular and

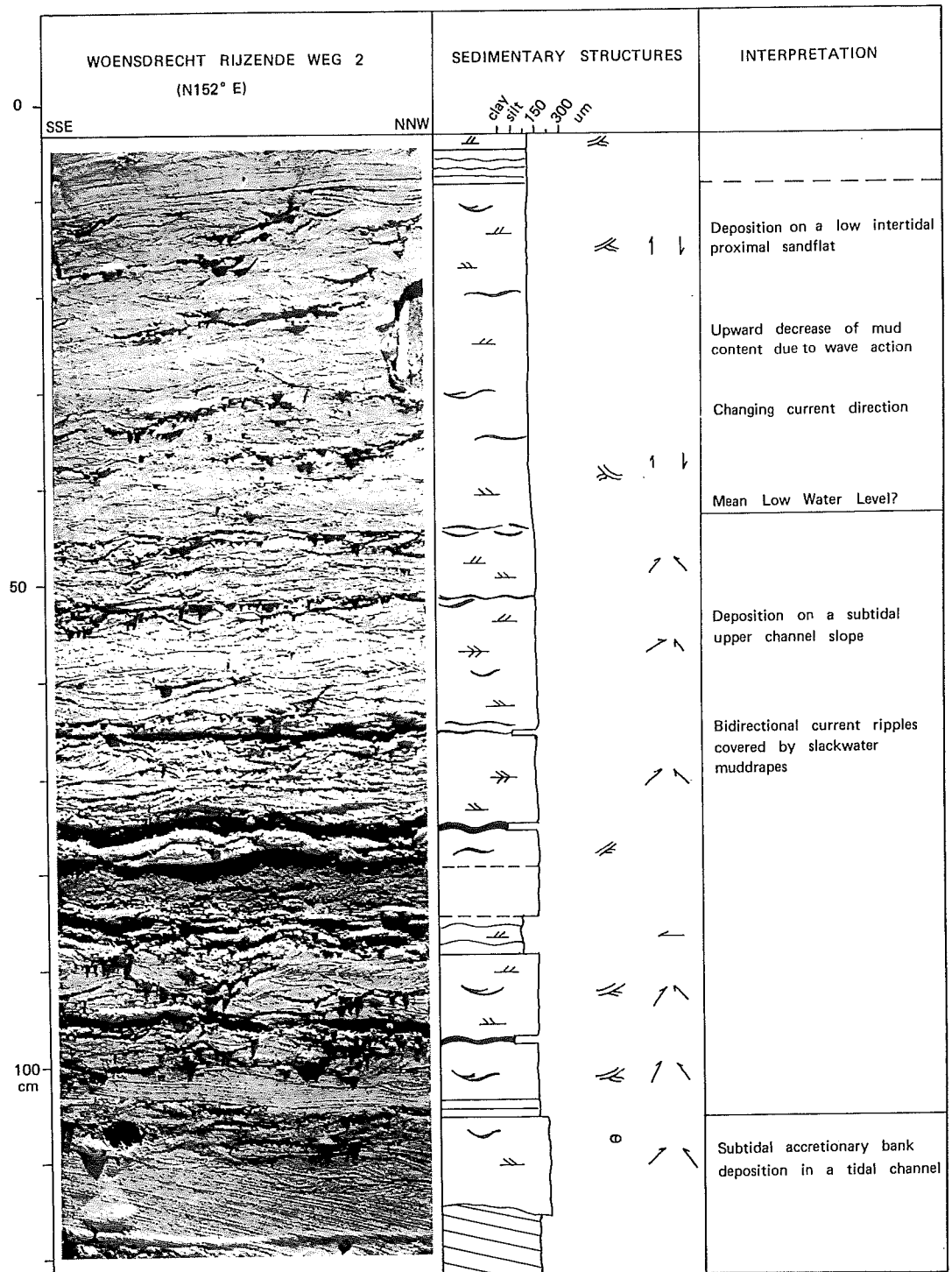


Fig. 3.15: Subtidal channel and (inter)tidal sandflat deposits with upward decreasing clay content. Woensdrecht Member at Woensdrecht Rijzende Weg.

tangential, bidirectional cross-bedding. The dominant current direction is to the westnorthwest. Clay-pebbles and reworked organic material are especially present above the erosional contact in OSD 4. The cross-bedded sets are maximal 20 cm high. The foresets are often covered with

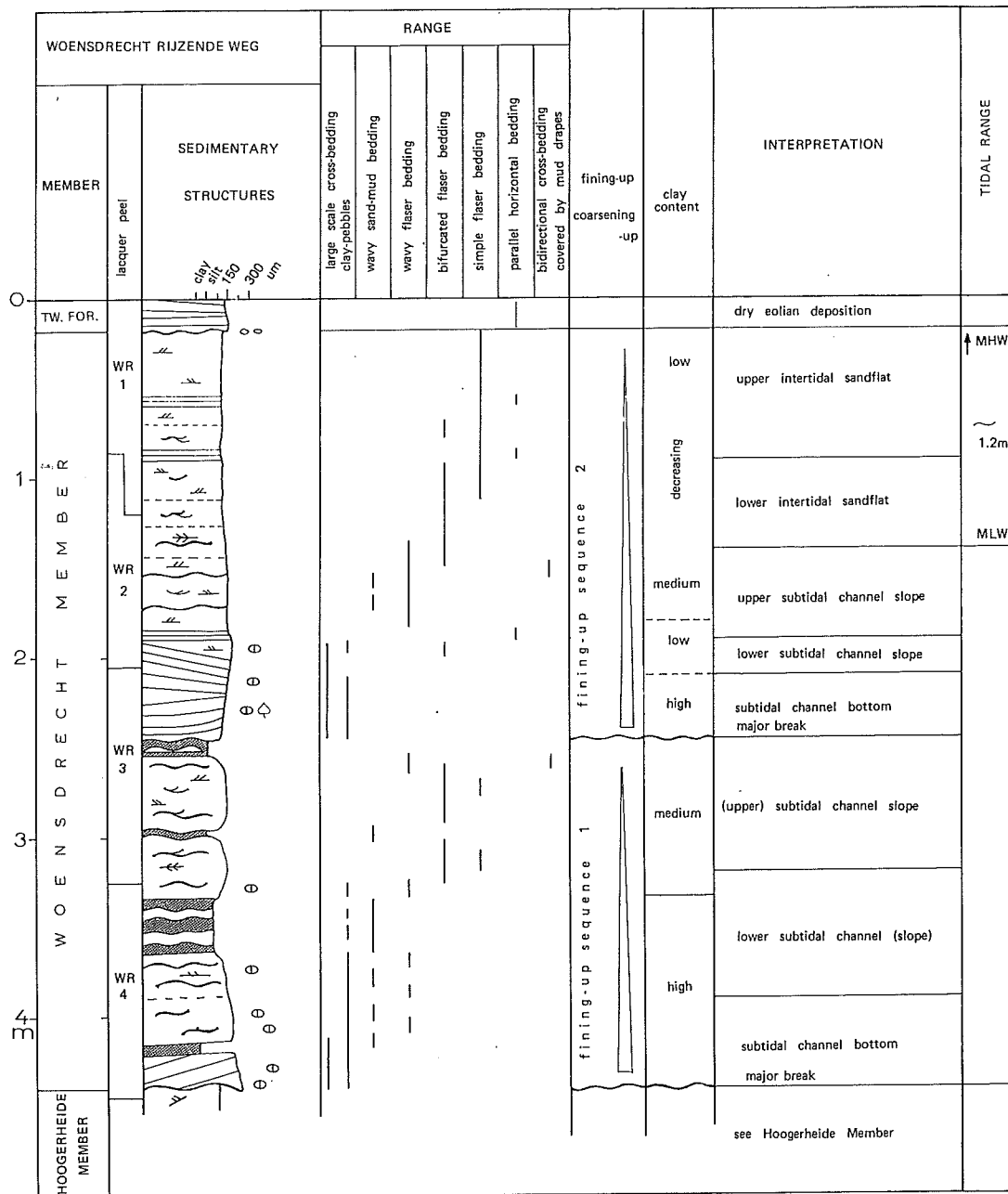


Fig. 3.16: Vertical sequence of channel and sandflat deposits and estimated tidal range in the Woensdrecht Member at Woensdrecht Rijzende Weg.

mud-drapes, perhaps locally arranged as clay-double layers (top OSD 4), and show reactivation surfaces (base OSD 2; top OSD 5). The individual cross-bedded sets have a length of a few meters at most. Thickening and thinning of the foreset-laminae in the set was not observed. However, steepening and flattening of the foreset-laminae and thickening and thinning of the set is present (not in the lacquer peels). Clay-laminae and small-scale bidirectional cross-bedding (herringbone cross-bedding) are common at the base of the large-scale cross-bedded sets.

Unit 3: The large-scale cross-bedded sets (unit 2) are suddenly replaced by wavy sand-mud bedding, lenticular bedding and small-scale

flaser cross-bedding. Clay-pebbles reflect the erosive character of the boundary (fig. 3.19: OSD 2). Wave ripple cross-bedding was found locally in 10 cm thick units which show a coarsening-up at the base and a fining-upward at the top (fig. 3.20: OSD 1). The imbricated internal structure and the stacking of the ripple crests illustrate the wave origin (fig. 3.19: top OSD 2).

Unit 4 consists of large-scale, trough cross-bedding, changing upwards into small-scale, trough cross-bedding, flaser bedding and parallel horizontal bedding (fig. 3.20: OSD 1). The large-scale cross-bedding and sandy nature of unit 4 is an isolated phenomenon as it changes laterally into wavy sand-mud bedding and laminated clay.

Interpretation

Several sedimentary structures in the Woensdrecht Member are characteristic of tidal processes (De Raaf and Boersma, 1971; De Vries Klein, 1971; Reading, 1980; Terwindt, 1981). These include:

1. bidirectional, large-scale and small-scale cross-bedding,
2. reactivation surfaces,
3. clay-drapes,
4. repeated alternations of sand and clay,
5. abundant clay-pebbles,
6. neap-spring-neap associated structures.

There are some differences between the exposures, which are probably related to differences in current velocity.

Woensdrecht Rijzende Weg (WR)(fig. 3.15, 3.16):

The sediments are finer grained, better sorted and contain more small-scale sedimentary structures in comparison to the Ossendrecht and Woensdrecht Hooghuis exposures. The two sequences are interpreted as two stages of tidal channel infilling with subsequent stacking of the sediments (fig. 3.16).

The large-scale cross-bedding at the base of the lower sequence is formed by westward migrating megaripples on the channel bottom (App. WR5). Due to channel migration wavy bedding and wavy flaser bedding developed on the subtidal channel slope (fining-up). Mud-draped ebb and flood current ripples are found up to the top of the sequence (=subtidal). Current direction was to the southsoutheast and northnorthwest in WR 3.

This subtidal deposition was interrupted by the formation of the upper channel sequence (fig. 3.16). First low-angle cross-bedding (top WR 3) was formed on the channel bottom. As the channel migrated, sediment accumulated on the channel slope in wavy sand-mud and wavy flaser bedding. The highest bidirectional mud-draped cross-bedding (=subtidal) is found approximately in the middle of WR 2 (fig. 3.15, 3.16). Above this level wavy flaser bedding changes into simple flaser bedding. The upward decrease in clay-flaser content is explained by the influence of wave action on higher, more exposed intertidal flats (Van Straaten, 1964). The parallel horizontal bedding (WR 1) is interpreted by upper flow regime deposition, formed during the emergence of the sandflat surface at low tide.

Current direction changes upward in the upper sequence. Northnorthwest-southsoutheast currents are replaced by more northeast-southwest currents, due to the change from subtidal channel into intertidal flat deposition.

Minimal tidal range can be approximated by the estimation of the mean low water level (MLW). The highest bidirectional mud-draped ripples (=subtidal) and overlying wave influenced decrease in flasers (inter-

tidal) allow designation of the MLW level in the middle of lacquer peel WR2 (fig. 3.15, 3.16). A mean high water level, based on marsh sediments or peat-beds, cannot be established, so a minimal tidal range of 1.2 m is assumed.

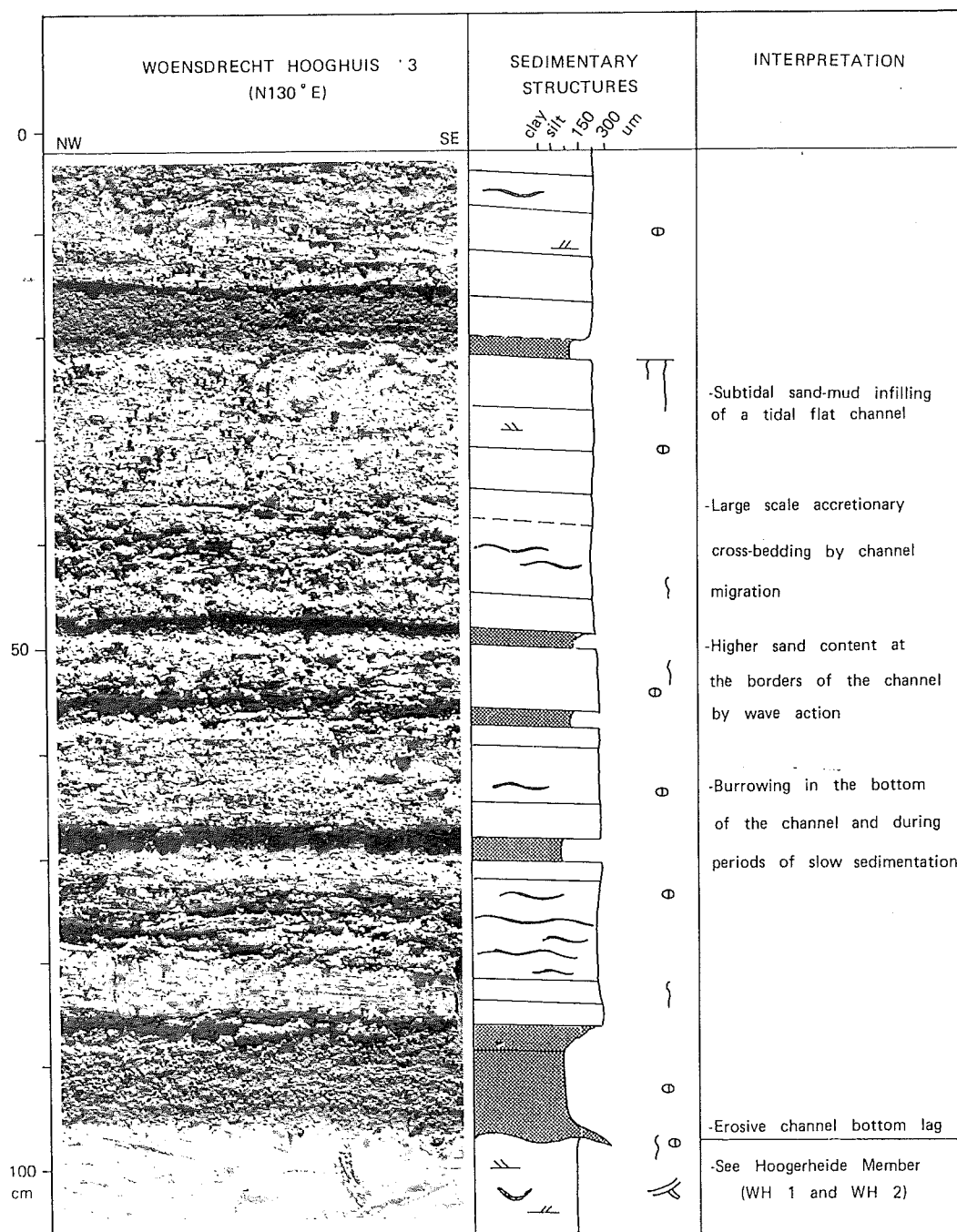


Fig. 3.17: Coarse-grained tidal channel base with low-angle cross-bedding and abundant clay-pebbles. Note the curved burrow in the bottom of the channel. Woensdrecht Member at Woensdrecht Hooghuis.

Woensdrecht Hooghuis (fig. 3.17):

The coarsely interlayered, low-angle sand-mud bedding is characteristic of relatively small tidal channels (Reineck and Singh, 1980). The clay-pebbles and coarse sand with one quartzitic sandstone pebble formed the lag deposit of the active channel. Animals at the channel bottom bioturbated the underlying Hoogerheide Member.

The large-scale unconformities in the sequence (see appendix) point to vertical stacking of channel sediments. The relatively sandy channel slopes may be explained by the winnowing action of waves. The fining-up and thinning-up of the beds towards the top reflect the final silting of the channel. The presence of well developed bioturbation levels at the top of the sequence points to a reduced sedimentation rate and a fairly high salinity. In combination with a change from low-angle cross-bedding to parallel horizontal bedding, the bioturbation might indicate an intertidal setting (Van Straaten, 1964), but MLW and MHW levels could not be designated.

Ossendrecht (fig. 3.18, 3.19, 3.20):

Unit 1 is interpreted as a subtidal deposit. The climbing ripple bedding may point to rapid infilling of a tidal channel, as was found in the upper part of the Hoogerheide Member in Woensdrecht Hooghuis and Woensdrecht Rijzende Weg.

Unit 2 (fig. 3.18, 3.20): The large-scale cross-bedding was formed by migrating megaripples in a 4 to 5 m deep tidal channel (Reineck and Singh, 1980). Current direction was dominant to the westnorthwest, probably caused by the ebb current. The subordinate flood current is reflected by reactivation surfaces in the ebb-dominated megaripples, by small-scale herringbone cross-bedding and some megaripple cross-bedding. The dominance of the ebb direction can be explained in an estuarine environment by additional river outflow or by the position in an ebb dominated channel.

Slack-water periods are registered as clay-drapes on foresets and bottomsets (fig. 3.18). The small-scale, herringbone cross-bedding at the base of the large-scale, ripple structures is interpreted as bottomsets, in which both ebb and flood currents are present.

The steepening and flattening of the megaripple foresets, together with the appearance (thickening) and disappearance (thinning) of megaripple sets, are attributed to neap-spring-neap tidal cycles in an estuarine environment (Terwindt, 1981; Visser, 1980). From neap to spring tide, currents accelerated and the set height and foreset angles increased. Deceleration of the current velocity from spring to neap tide caused the reverse.

The estuarine channel (unit 2) was filled in two phases (stacking of channel sediment), separated by an erosive contact with a clay-pebble lag deposit (base OSD 4). The sedimentary structures in unit 2 resemble the (sub)recent estuarine sediments of the Haringvliet (Oomkens and Terwindt, 1960; Terwindt, 1971; Terwindt, 1981). Channel depth (circ. 5 m) and set height (circ. 25 cm) at Ossendrecht are, however, less than in the Haringvliet. The sedimentary structures of the (sub)recent Oosterschelde are much larger (Terwindt, 1981; Van den Berg, 1986).

Unit 3: The major break between unit 2 and 3 may be regarded as a paleo mean low water level (fig. 3.19). The ebb directed, mud-draped (subtidal), large-scale cross-bedding below the break; the wave ripple bedding above the break, arranged in an overall fining-upward sequence, support this view. The transition from large-scale into small-scale structures is interpreted as the transition from tidal channel into channel slope or tidal flat.

Compared to the sediments below the MLW level the intertidal sediments

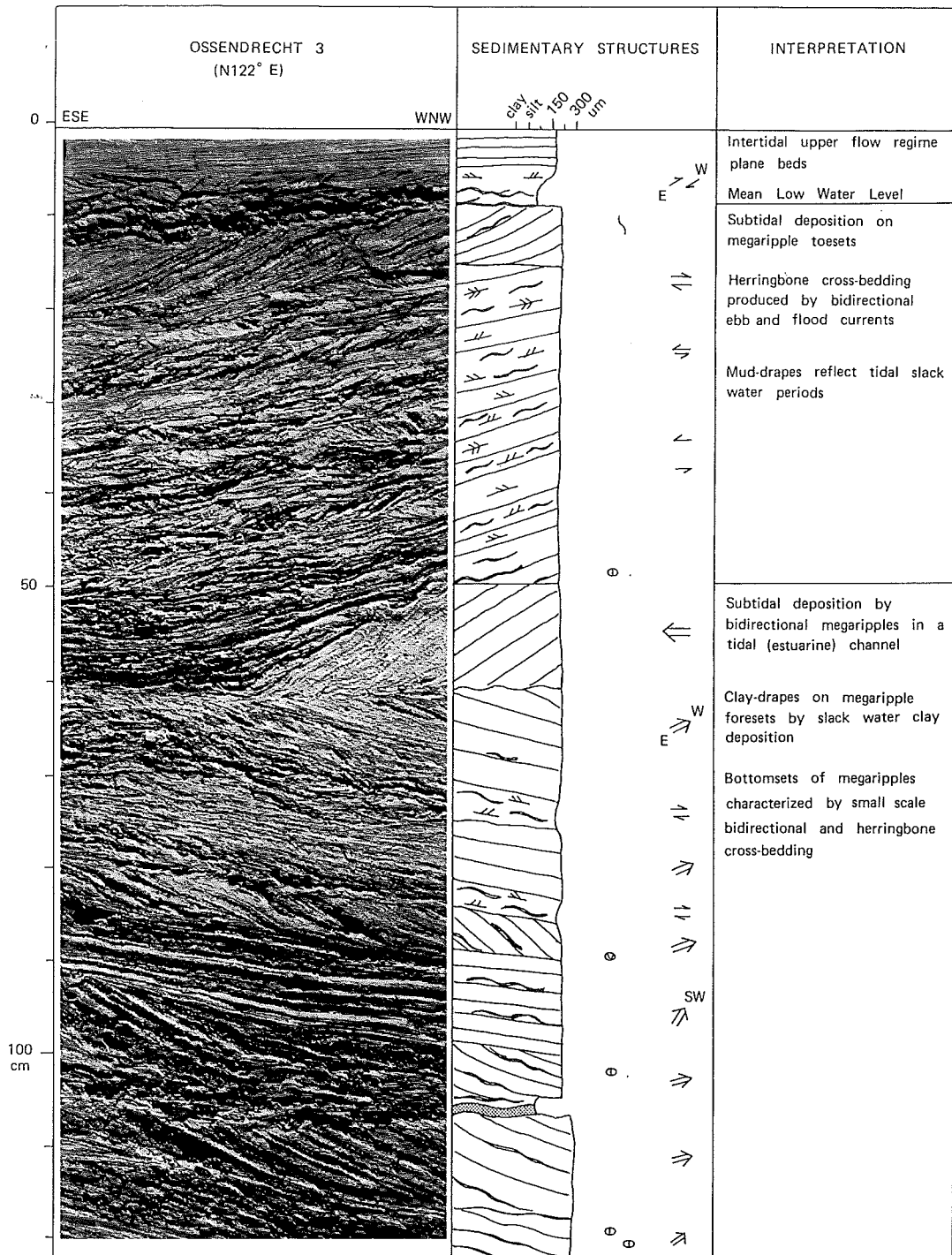


Fig. 3.18: Subtidal channel deposits with bidirectional large-scale and small-scale cross-bedding. Abundant mud-drapes formed during slack-water periods. Woensdrecht Member at Ossendrecht.

on channel slopes are often more clayey (Van Straaten, 1964). The wave ripple structures (fig. 3.19: top OSD 2) illustrate the intertidal conditions (Van Straaten, 1964). The small-scale coarsening-up/fining-up sequences, in which these wave ripples were found, may have been

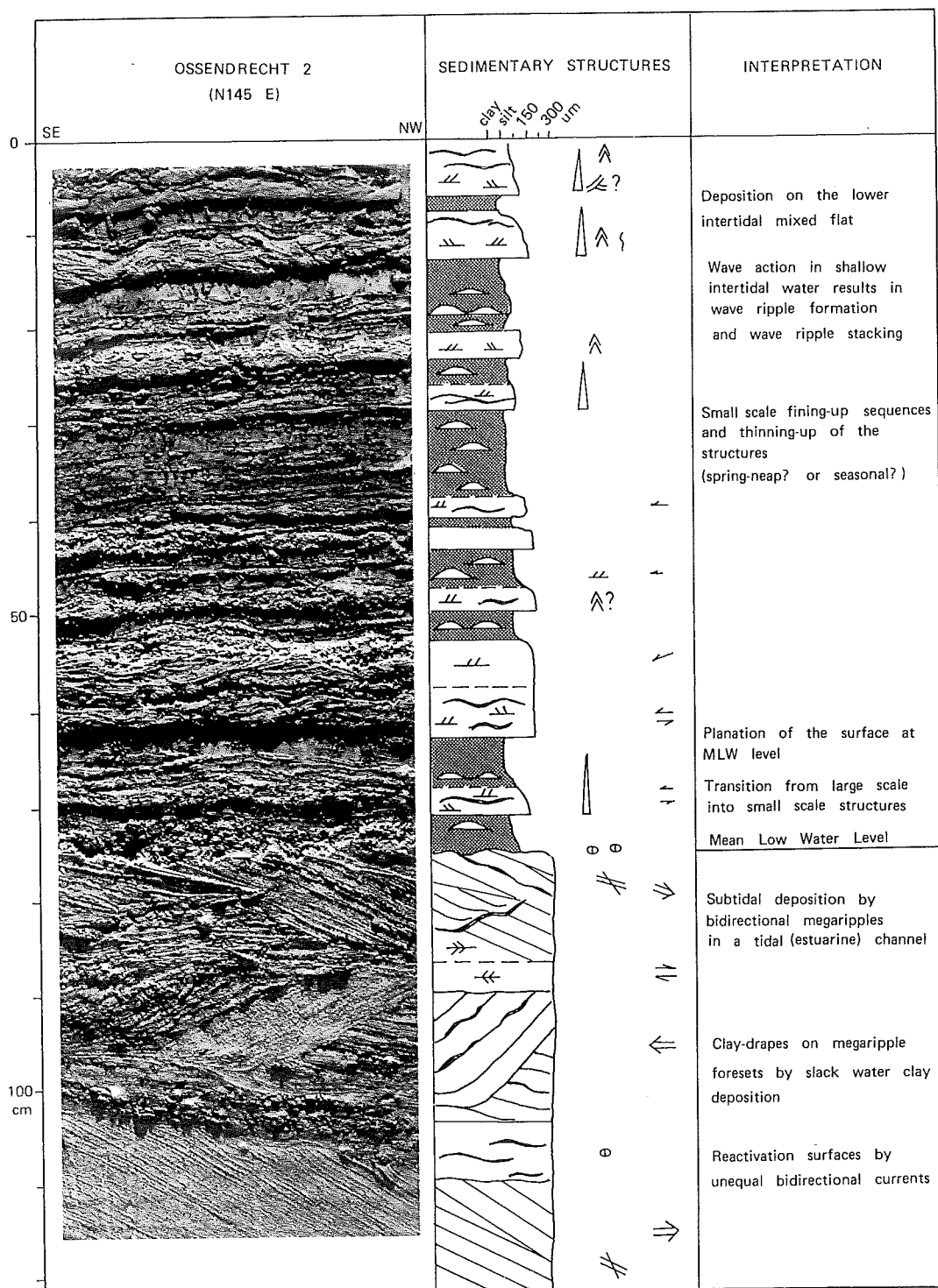


Fig. 3.19: Subtidal, bidirectional channel deposits with clay-drapes on the foresets and (inter)tidal mixed flat deposits with wave ripple bedding. The break in the deposition is interpreted as the mean low water level. Woensdrecht Member at Ossendrecht.

formed by neap-spring-neap tidal cycles or by seasonal, turbulent and fair weather periods.

Unit 4: The large-scale cross-bedded unit is a local phenomenon in an overall fining-up sequence (fig. 3.20). It is laterally equivalent to a laminated sand-clay bed, which forms a more or less continuous layer in the exposure (see App.). The large-scale, trough cross-bedding, was probably formed by megaripples in a small tidal channel. The restricted extent of the channel sediment points to limited lateral migration. Therefore, unit 4 is interpreted as a local tidal gully in an intertidal mudflat environment. Current direction in this intertidal channel was to the southwest, at right angles to the stream direction in the main channel below (unit 2). These intertidal gullies often drain the intertidal flat during ebb into the subtidal channel (Van Straaten, 1964). The fining-up sequence and thinning-up of the sets in the upper part of unit 4 indicate the final silting of the gully. Shallow water conditions resulted in upper flow regime conditions and caused the formation of parallel, horizontal bedding (top OSD 1).

Tidal range is based on MLW and MHW estimations (fig. 3.20). A constant sea-level is assumed, since a continuous sedimentary sequence (fining-upward) is present, which probably formed in a short period of time. The mean low water level is postulated from the presence of mud-draped ebb oriented ripples, wave ripples and a major break in the sedimentary structures and grain-size. The MHW level is unknown as crinkly bedded salt-marsh sediments or peat-beds are absent. The tidal range estimation is therefore less reliable than in Meerle (§3.3.4). As the top of the sequence is still of an intertidal character, tidal range is more than 1.7 m, not corrected for compaction.

Synthesis of the three exposures

The three exposures are characterized by fining-upward sequences with tidal channel sediments at the base and tidal flat deposits at the top. Sequential differences between the exposures seem to be related to differences in current velocity and wave influence. Channel depth is more or less constant (5-7 m).

The large-scale cross-bedding in relatively thick sets and coarse sand at Ossendrecht were formed by megaripples in estuarine channels with high current velocities (fig. 3.20). Channels with medium currents are characterized by thick interlayered bedding and lateral accretion cross-bedding (fig. 3.17: Woensdrecht Hooghuis). The low velocity tidal flat channels were filled with finer sand and small-scale sedimentary structures (fig. 3.16: Woensdrecht Rijzende Weg).

Lateral channel migration or decreasing currents in the channels led to a fining-upward sequence. Wave action was probably better registered in the tidal flat channels and adjacent tidal flats (WR), than in the larger, current dominated, estuarine channels (OSD). The top filling of the smaller channels and overlying tidal flat deposits are therefore characterized by a short, wave induced coarsening-up interval and decreasing heterolithicity (fig. 3.16: WR). The presence of wave-formed sequences points to a seaward (=proximal) setting of the tidal environment (Van Straaten, 1964).

The large-scale cross-bedded sets in the tidal channels are formed by bidirectional currents (fig. 3.20). The west to northwest current was dominant and probably reflected the ebb current (on paleogeographic grounds). Ebb dominated sediments are especially found in the estuarine channels, because of the connection to a fluvial system. In the overlying intertidal sandflats southwest-northeast currents were found (OSD, WR). This change in current direction was probably caused by the

difference between ebb channel flow and overbank flood water flow over intertidal flats (Reading, 1980).

The estuarine environment is characterized by mixing of water and sediment. The minor presence of bioturbation in the sediments was caused by variations in salinity and a high sedimentation rate, which hampered colonisation of the sediments by burrowing organisms (König, 1976). Tidal range was estimated between 1.2 and over 1.7 m.

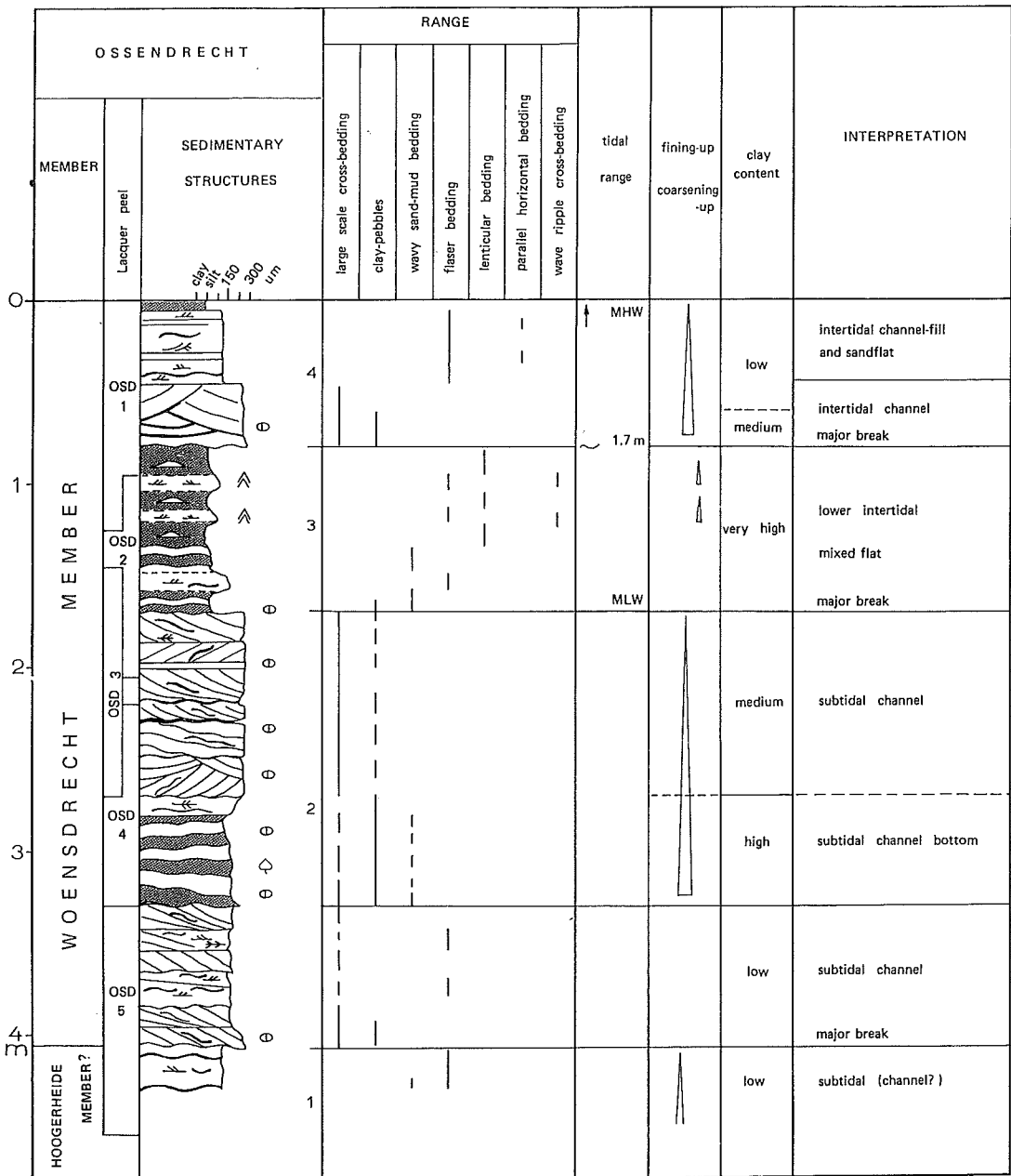


Fig. 3.20: Micro/mesotidal sequence with coarse-grained tidal channel and mixed tidal flat deposits. The intertidal channel is a local phenomenon. Woensdrecht Member at Ossendrecht.

Last stage clay deposition (fig. 3.21):

The top of the Woensdrecht Member is often formed by a continuous clay-layer, which extends laterally into the top of the Turnhout Member in the east (fig. 2.3, 2.6) (not present in exposure Woensdrecht Rijzende Weg). The lower boundary of the clay can be transitional or very sharp. The transitional boundary is found in tidal channel fillings with fining-up and thinning-up sequences (e.g. Woensdrecht Hooghuis), where the clay-layer represents the final phase in the tidal sequence.

At Korteven a very sharp boundary separates clean, white, tidal flat sand from overlying, stagnant water clay with high lutum content (fig. 3.21). Decreasing input of clastic sediment resulted in peat formation

in a wet, fresh water environment (dominance of *Alnus* pollen, see §4.3.1). Later the peat drowned gradually and with increasing current velocity, well laminated, tidal, brackish water silts were formed (high *Chenopodiaceae* content). The sharp boundary between clay and underlying sands suggests a sudden break in the sedimentary sequence, which is illustrated by the presence of a peat-layer or soil (Geol. Survey of The Netherlands: borings 49G-66, 49G-75; Van Dorsser, 1956, p. 29 (soil), p. 33 (charcoal); Huyzer and Van Toor, 1986). The sudden decrease in transport capacity can be explained by a damming or silting of tidal channels in the estuarine environment. This may cause a decrease in tidal range and a local drop in water level. A regional sea-level change, however, cannot be excluded. The decline in water level is expressed on former high sedimentary surfaces (tidal sandflats) by soil formation (see Van Dorsser, 1956, p. 29: soil

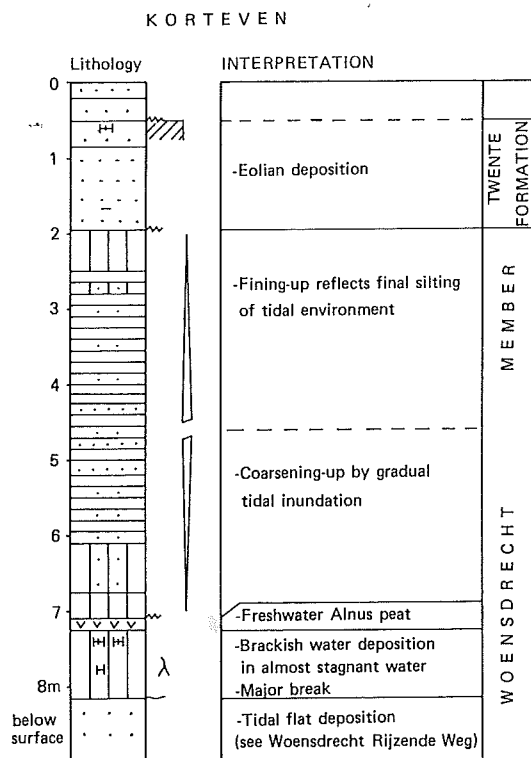


Fig. 3.21: Last stage deposition in the upper part of the Woensdrecht Member.

profile in the top of the sand, below overlying loam). In lower lying places conditions for peat formation were more favourable.

The water level drop was registered best in the most seaward part of the inshore tidal environment (Woensdrecht Member). High intertidal sandflats fell dry here and show a clear sedimentological break. In the landward estuarine environments to the east sediments are generally more clayey (Turnhout Member) (Reading, 1980, fig. 7.45). A temporary drop in water level was registered there as a peat-layer or soil horizon between clay-beds, or was not registered at all.

Conclusion:

The Woensdrecht Member was formed in an inshore, micro- to mesotidal (estuarine) environment. Wave action points to a seaward setting of the tidal flats and channels. A sudden drop in local water level caused peat formation and clay deposition in a more sheltered environment.

3.3.7 Gilze Member

The member consists of fine to medium, locally medium coarse sands with loam, clay and peat-beds (§2.5.8). Three units could be distinguished.

Description of the sedimentary structures (fig. 3.3, 3.4, 3.22)

Unit 1 (Appelenberg Sands) is the fine-grained lower part of the member with swift alternations of sand, peat and clay-beds (Appelenberg, Chaam Kapel, Meerle Slikgat base). Parallel horizontal bedding is the dominant bedding type.

Unit 2 (Gilze Clay) is also fine-grained, but characterized by thick fining-upward sequences, capped by a clay-layer (Nieuwmoer, Gilze, Snijders-Chaam). Parallel horizontal bedding, small-scale cross-bedding and some large-scale cross-bedding are the most characteristic bedding types.

Unit 3 (Alphen Sands) consists of medium coarse sand (Weelde, Ravels, Zwart Goor, Meerle Slikgat). Clear fining-upward sequences are absent. Massive bedding, parallel horizontal bedding and large-scale (trough) cross-bedding are regularly found. Clay-pebbles and peat-lumps are a common constituent (fig. 3.22).

Interpretation

The rapid lateral and vertical facies changes in the Gilze Member restrict the environmental interpretation. The fine to medium coarse sand, fining-upward sequences, reworked organic material and the intercalated humic to peaty soil horizons in the member may point to a fluvial environment. Eolian deposits have not been found, although they seem to be present in equivalent deposits east of the investigated area in the Central Graben (Bisschops et al., 1985). However, distinction between eolian and fine-grained fluvial deposits in borings can be difficult.

Unit 1: The thin (0.2-0.3 m) sand-units have an erosive lower and abrupt upper boundary and (wavy) parallel horizontal bedding. They are interpreted as floodplain overbank deposits (McKee et al., 1967) or shallow channel deposits, beyond the active river courses (Reading, 1980; Van Alphen, 1984 in: Bisschops et al., 1985). The clay- and loam-beds were formed by settling from suspension in a backswamp environment. During periods with limited supply of clastic sediment peat-beds could develop and gyttja-like beds were locally deposited in limnic environments (fig. 3.4: Appelenberg).

Unit 2: The large-scale fining-upward sequences stratigraphically overlie unit 1. The sands with associated small and large-scale cross-bedding are interpreted as fluvial channel deposits. The thick units point to deep channels (9.5 m at Gilze; 6 m at Nieuwmoer), which locally incised into the underlying Turnhout Member (fig. 3.4). The gradual transition of sand into clay and the large lateral extension of the clay-bed at Gilze probably reflect deposition by a meandering river. The clay at the top of the fining-up sequence is interpreted as a backswamp deposit outside the active river course. Swamp forests dominated by *Alnus* and other warm temperate species gave rise to local peat formation.

Unit 3: The large-scale, low-angle cross-bedding in medium coarse sand is interpreted as megaripple bedding formed in fluvial channels (fig. 3.3, 3.4: Weelde upper part, Zwart Goor, Meerle Slikgat upper part). The absence of fining-up sequences and clay-beds points to rapid migration of the channel systems, which is more characteristic of braided

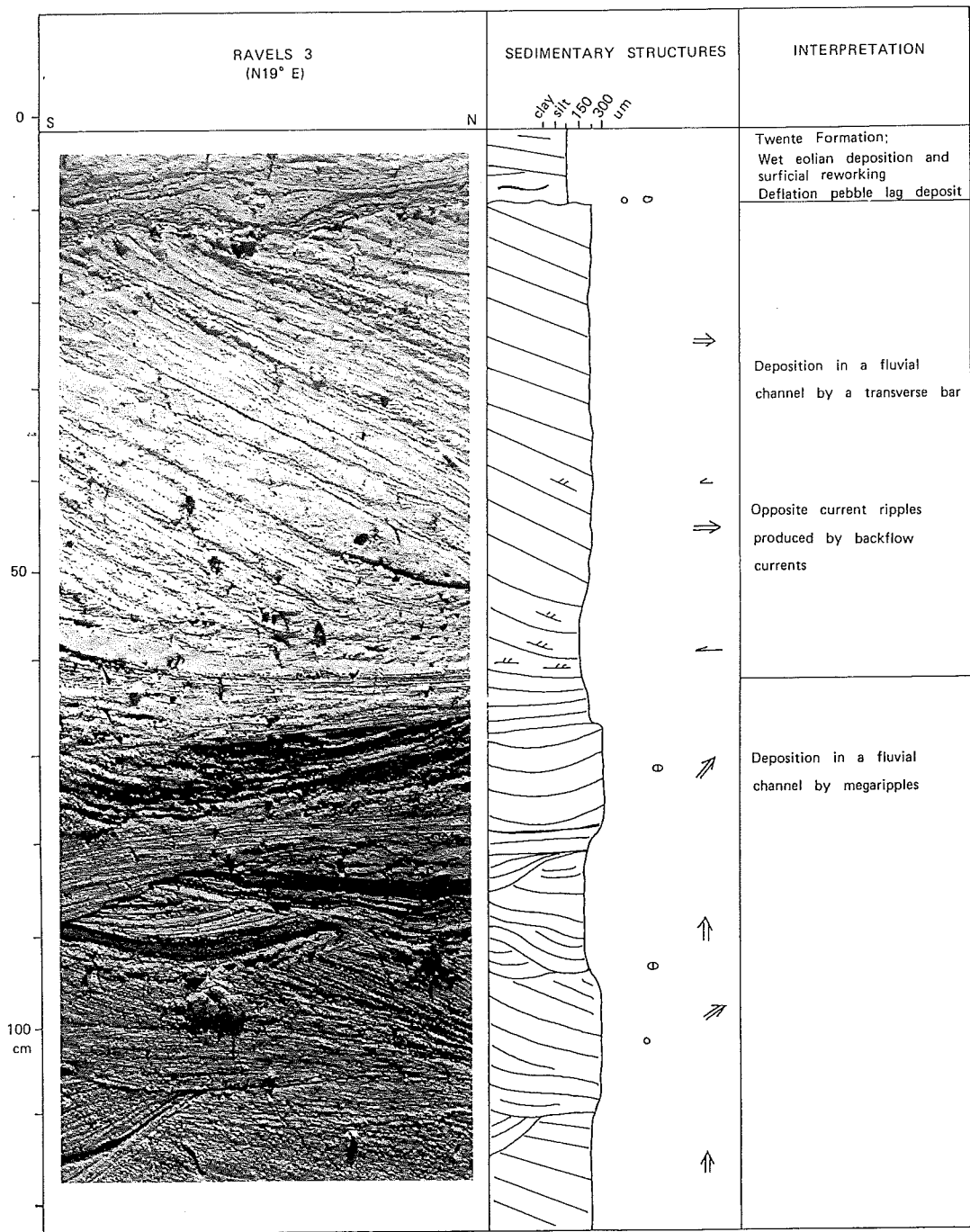


Fig. 3.22: Fluvial, braided deposition by megaripples and transverse bars in the Gilze Member at Ravels. Note the backflow ripples at the base of the large-scale foresets.

river systems (Vandenberghe et al., 1986). The large-scale involutions (50-100 cm)(cryoturbations?) at different levels within unit 3 in Weelde (not in the appendix) indicate periglacial sedimentary conditions (Vandenberghe and Krook, 1981).

Unit 3 was studied in detail in exposure Ravels (fig. 3.22). Large-scale, trough cross-bedding is dominant (see app. Ravels 1, bed 7). The

troughs are broad (approximately 6 m wide) and shallow (0.5 m deep). Large-scale cross-bedding, backflow ripple cross-bedding and climbing ripple cross-bedding are found in the trough structures. Reworked plant material and clay-pebbles are common (fig. 3.22). The trough cross-bedding at Ravels is interpreted as channel cut-and-fill structures in a braided river system (Picard and High, 1973; Singh, 1977; Reineck and Singh, 1980). The shallow troughs at Ravels generated during high discharges. A subsequent decrease of the current velocity caused the lateral filling of the channel with medium coarse sand (210-300 μm). Backflow currents produced backflow ripples at the base of the large-scale cross-bedding (fig. 3.22). The cut-and-fill structures at Ravels suggest a stream direction to the westnorthwest. During low discharges fine sand, silt and humic material was deposited on the trough slopes. This water-saturated sediment locally slumped towards the centre of the trough (see App. Ravels 1, left of the middle).

Conclusion:

The Gilze Member is a complex of three units which developed in different sedimentary environments. The lower unit 1 is deposited in a fluvial environment with small river channels, floodplain overbank deposition, backswamps and lakes. Unit 2 is interpreted as a meandering river deposit consisting of channel sand and backswamp clay and peat. The coarser grained upper part of the Gilze Member (unit 3) was formed by large, shallow (partly westnorthwest flowing), sandy braided rivers systems.

3.3.8 Bavel Member

Description of the sedimentary structures (fig. 3.3, 3.23)

The Bavel Member in clay-pit Bavel is subdivided into two lithological units. The lower unit 1 consists of gray, calcareous clay. Intercalated sand-beds show weakly developed, wavy parallel bedding (fig. 3.3). Unit 2 consists of well-sorted sands, erosively overlying the clay. The fine sand (105-150 μm) at the base of unit 2 is characterized by small-scale cross-bedding and well-developed, climbing ripple cross-bedding (fig. 3.23). The upper part of unit 2 is coarser grained (150-210 μm) and separated from the fine sand by a lag deposit with clay-pebbles, wood fragments and fine gravel. Sedimentary structures are dominated by large-scale, trough cross-bedding. Sediment becomes finer grained to the top (fining-up) and set height decreases (thinning-up).

Interpretation

The sedimentary structures of the Bavel Member are associated with fluviatile depositional environments.

Unit 1: Thick clay-beds can be formed in backswamp environments or as clay-plugs in cut-off channels of a meandering river (Reineck and Singh, 1980). The clay is very calcareous, plastic and contains no soil horizons or bioturbation by roots. Therefore, deposition did not occur in a backswamp environment, but more probably in a channel cut-off of a meandering river in a warm temperate climate (chapter 4). The channel cut-off was quickly filled with suspended sediment (clay, silt, fine sand) introduced by overbank flows (no decalcification, no vegetation, limited physical ripening). The large thickness of the clay-plug points to a depth of the abandoned channel of more than 10 m. This deep channel eroded the Gilze Member between Snijders-Chaam and Bavel (fig.

3.3). In a newly excavated clay-pit the sand-beds in the thick clay-unit were better developed. They revealed abrupt alternations of sand and clay, some draping of clay-laminae on small-scale current ripple foresets and opposed current ripple cross-bedding approximately 50 cm apart. These features might reflect fresh water tidal influence during the filling of the meander cut-off.

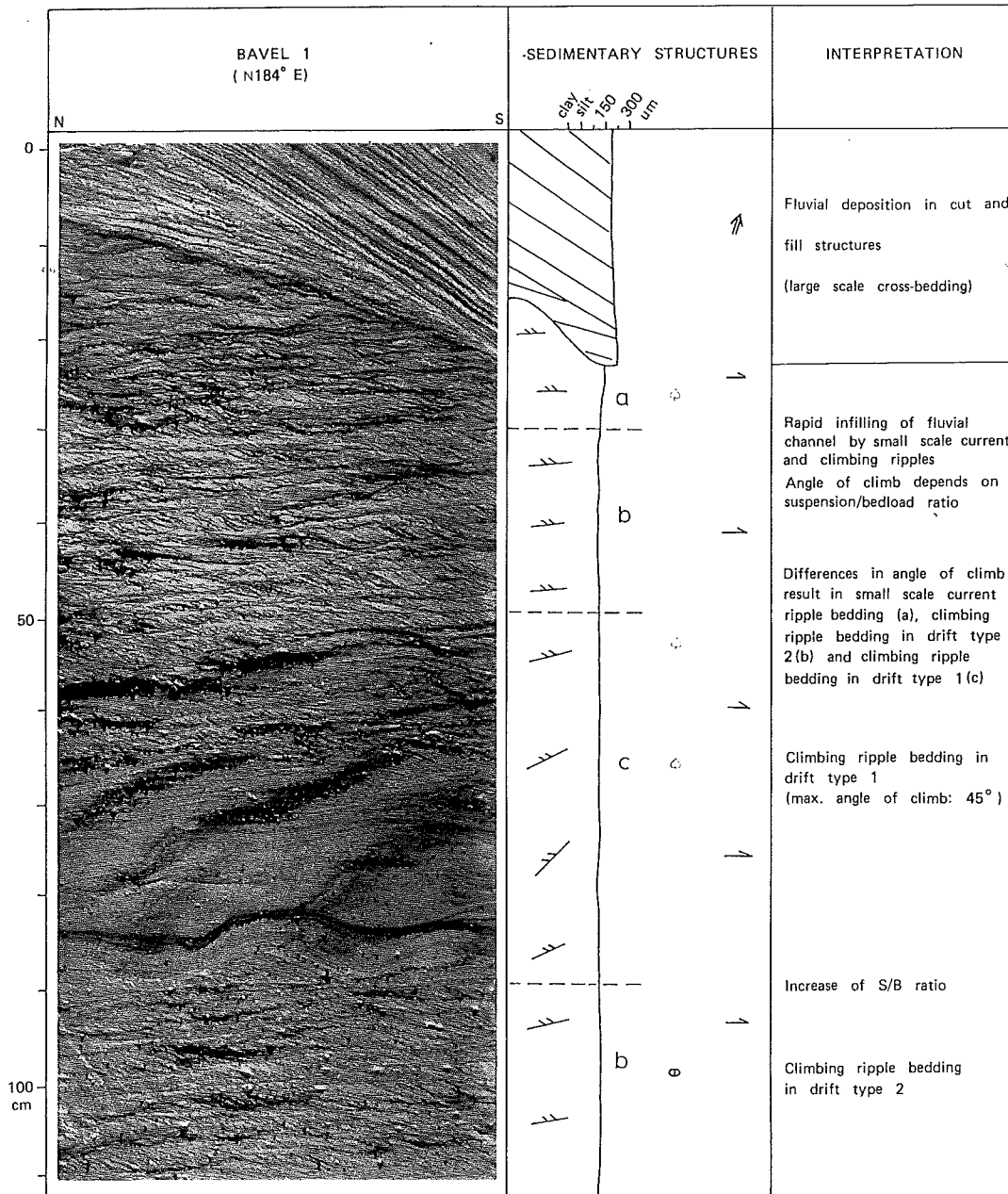


Fig. 3.23: Well developed climbing ripple bedding, truncated by large-scale cross-bedding in a fluvial channel of the Bavel Member at Bavel.

Unit 2: The sedimentary structures were formed by megaripples, small-scale current ripples and climbing ripples in a fluvial channel. After the underlying cut-off channel was filled with clay (unit 1), a new (meandering) river channel eroded part of the clay-plug. Filling first

occurred with fine-grained, well-sorted sands. The small-scale current ripple and climbing ripple beds are interpreted as pointbar deposits of a southsouthwest flowing river course (Reineck and Singh, 1980). Later, medium fine sands were deposited in cut-and-fill structures. The large-scale, megaripple trough cross-bedding indicates a more western stream direction then. The Bavel Member was probably formed along the southwestern margin of a meander belt, since no sediments have been found southwest of Bavel. The southeast-northwest oriented floodplain occurred predominantly northeast of the Gilze-Rijen fault system and locally crossed this fault at Bavel (Bisschops et al., 1985, fig. 21).

3.3.9 Middle- and Late-Pleistocene formations

3.3.9.1 Sterksel Formation

Description and interpretation of the sedimentary structures (fig. 3.4)

The Sterksel Formation in boring Appelenberg is characterized by medium coarse, moderately well-sorted sands. The interpretation is hampered by the isolated position of the unit in the study area (fig. 3.4). The parallel horizontal and low-angle, large-scale cross-bedding are interpreted as megaripple foreset structures. The uniform vertical sequence is explained by stacking of fluvial channel sediments. The channel deposits fill a more than 5 m deep valley eroded into the underlying Gilze Member (fig. 3.4).

East of the investigated area extensive beds of equivalent channel sediments have been found in the Central Graben (Bisschops et al., 1985). This widespread occurrence can be explained by rapid channel migration, which is more characteristic of sandy, braided river systems (Allen, 1965).

3.3.9.2 Eindhoven Formation

Description and interpretation of the sedimentary structures

The Eindhoven Formation consists of loamy, fine to medium coarse sands. The small-scale cross-bedded units (fig. 3.4: Wernhout Maalbergen, Achtmaal) were probably formed by small current ripples in a fluvial environment. Since internal, structural evidence is weak, the fluvial origin is deduced mainly from the geomorphological and stratigraphical context (Reading, 1980). The scarcity of large-scale cross-bedding may be explained by fluvial deposition in relatively small river channels (fig. 3.4: Wortel: current direction northnorthwest). The dominance of parallel horizontal bedding can be related to ephemeral fluvial activity (Reineck and Singh, 1980), to floodplain overbank deposition along active shifting rivers (McKee et al., 1967) or to a combination of fluvial and eolian deposition (Vandenberghe and Krook, 1985). The fining-up sequences (Achtmaal, Wernhout Maalbergen) are locally capped by peat- and loam-layers (fig. 3.3: Bolck). The high ratio of channel sediment versus fine backswamp sediment suggests combing of the floodplain by low-sinuosity, sandy braided rivers (Allen, 1965). The characteristic silt component in the deposits is interpreted by reworking of eolian material (Van den Toorn, 1967; Bisschops et al., 1985).

3.3.9.3 Twente Formation

Description and interpretation of the sedimentary structures

The Twente Formation consists predominantly of fine to medium fine sand. Medium coarse sand, loam-beds and pebble-layers occur locally. The stratigraphical and environmental interpretations are based largely on Van der Hammen et al., (1967), Vandenberghe (1985) and Schwan (1986).

A gravel-bed, at the base of the formation (App. Beerse Dakt), is correlated with the Gilze gravel deflation lag of Weichselian Lower Pleniglacial age (Vandenberghe, 1985). The large-scale, low-angle cross-bedded medium fine sand above the Gilze gravel is interpreted as eolian sediment, deposited in low dunes or filling former topographical depressions. This sand is succeeded by a massive silt-layer and wavy, parallel bedded sand (fig. 3.3: Beerse Dakt, Merksplas Strafinrichting, Beerse Blak). The silt-bed is probably equivalent with the "Brabantse loam" of Weichselian age (Van den Toorn, 1967; Bisschops et al., 1985). The high topographical position of this silt-layer on the Campine microcuesta points to a primary eolian transport, but local concentration in standing water may have occurred as well (Bisschops et al., 1985; Haest et al., 1986).

The "Brabantse loam" is locally deformed and truncated by a second pebble-layer (fig. 3.4: Weelde), formed by surficial runoff and deflation, which is correlated with the Beuningen gravel-bed of Weichselian Upper Pleniglacial age. Loamy sands above the Beuningen gravel with a large regional extent are interpreted as eolian sand-sheet deposits and correlated with the Older Coversand II (Van der Hammen et al., 1967). The alternating bedding of sand and silt laminae is explained by seasonal variations in wind velocity (Schwan, 1986).

A humic soil or peat-layer on top of the loamy sands witnesses a period of surface stability (fig. 3.4: Weelde and Ossendrecht). The soil is equivalent to the Usselo-layer of Allerød age. After the Allerød period renewed local eolian sedimentation occurred at Ossendrecht and Weelde, which is correlated with the Younger Coversand II. The large-scale, low-angle, trough cross-bedding and parallel horizontal bedding, point to the deposition in low dunes at Ossendrecht. The parabolic dune forms indicate a southwest-northeast wind direction (Meys, 1974).

3.4 Paleoeological interpretation of the Early-Pleistocene deposits in western Noord-Brabant.

S.J.P. Bohncke and C. Kasse

Summary

Transformed pollendiagrams, in which each biozone is represented by a bar diagram consisting of ten widely defined vegetation units (physiognomical groups) together with macro remain analyses provided a generalized picture of the paleoenvironmental development for the Turnhout and Woensdrecht Members.

The lithologically and sedimentologically established tripartition (thick lower clastic unit, organic unit, thin upper clastic unit) could be recognized in the paleobotanical record.

Both clastic units show lateral changes in the pollen assemblage that can be interpreted by a northern increase of waterdepth, salinity or increased distance to the zone with upland forest, heath and floodplain forest.

The levels with increased Chenopodiaceae pollen (physiognomical group 2) have been interpreted as representing tidal litter zones. Tidal litter zones established due to tidal action along the southern rim of the basin, at places with temporarily emerging substratum in the understory of an intertidal herbaceous marsh.

The species composition of the intertidal marsh at the western side of the investigated area, preceding and overlying the organic level, indicate mesohaline conditions. Eastwards oligohaline to nearby fresh water conditions prevailed.

During the maximum of the peat formation the area must have been characterized by an extensive herbaceous marsh, dominated by *Typha* spp. and intermingled with shallow pools with stagnant fresh water. In some places soil formation took place in the emerging substratum. The local presence of alder flood plain forest could not be established. It is supposed that these were located south and eastwards of the study area.

3.4.1 Introduction and methods

Clayey and peaty intervals within the Turnhout and Woensdrecht Members have been subjected to pollen analyses. Besides biostratigraphical information, the pollen data from these Early-Pleistocene deposits yield information about changes in the paleoenvironment. To facilitate the evaluation of the data obtained, the following procedure has been developed.

The pollen diagrams have been subdivided into zones. For this subdivision major changes in the species composition as well as lithological changes have been taken into account. One zone in the pollen record is considered as a more or less stable phase in the environmental evolution, representing a single specific biotope. It is assumed in this study that climatic changes within the members are only marginal and that changes in the pollen record are also determined by changes in the depositional environment.

A second assumption is that within the Turnhout and Woensdrecht Members only one phase with increased *Alnus* values is present. Lithologically this level is characterized by an increase in organic content (humic clay or peat). This level forms a base for litho/biostratigraphical correlation.

In order to characterize the biotope represented by one pollen zone, the pollen types have been assigned to ten widely defined vegetational units (or physiognomical groups) in accordance with the occurrences of their present-day relatives (Van der Burgh, 1983). Throughout a pollen zone, the percental values of all pollen and spore types belonging to one specific physiognomical group have been added up. Subsequently the total of the percental values of the physiognomical groups has been fixed at 100% and the individual contribution of each group has been recomputed. The results have been plotted in bar diagrams. In this manner each biozone within a lithostratigraphic unit is simplified into a diagram consisting of ten bars (the physiognomical groups). The height of the bars is related to the percental contribution of the group to the total of 100%.

In this conception it should be possible to give a short overall characterization of that specific biotope and subsequently group these biotopes in a logical sequence, both laterally (space) and vertically (time), in order to compose a three-dimensional paleoenvironmental picture. The bar diagrams have been arranged in two north-south and one east-west cross-section, in accordance with the lithological (fig. 2.5, 2.6) and sedimentological cross-sections (fig. 3.3, 3.4). It is assumed that in this way gradients in the paleoenvironment would show up, which could subsequently be interpreted in spatially related more or less contemporaneous biotopes. Changes in these biotopes in time (vertical changes in the bore sections) can then give an indication of the processes that have exerted their influence on the study area during the period of deposition of one specific lithostratigraphic unit. It must be stressed that the sedimentological and paleobotanical record of the boreholes and exposures may contain hiatuses. The occurrence of non-deposition or erosion, however, can provide information that is of significance for the reconstruction of the paleoenvironment.

3.4.2 Grouping of the pollen and spores

Ten physiognomic groups have been designated in this study, representing most of the variation in the biotopes during deposition of the Turnhout and Woensdrecht Member. These groups are:

1. salt-marsh and mudflat vegetation: e.g. *Armeria*, *Hystrichosphaeridae*.
2. tidal litter zone vegetation: e.g. *Chenopodiaceae*, *Artemisia*, *Compositae tubuliflorae*.
3. fresh water vegetation, subaquatic and floating plants: e.g. *Algae*, *Myriophyllum*, *Nuphar*, *Umbelliferae*.
4. herbaceous shore vegetation: herbs from the telmatic zone in fresh water environments: e.g. *Typha*, *Gramineae*, *Cyperaceae*, *Chamaenerion*, *Filicales*.
5. carr vegetation: mostly trees and shrubs (ferns) occurring in stagnant shallow water or damp soils: e.g. *Pterocarya*, *Alnus*, *Betula*, *Salix*.
6. floodplain forest: trees and ferns from damp soils adjacent to streams, which are periodically flooded: e.g. *Alnus*, *Pterocarya*, *Fraxinus*, *Osmunda*.
7. upland forest: forest on relatively dry, well drained sites: e.g. *Quercus*, *Betula*.
8. coniferous forest: forest on dry, nutrient poor soils: *Pinus*, *Tsuga*, *Sciadopitys*.
9. heath: dwarf-shrub vegetation dominated by heather: *Ericaceae*, *Juniperus*.
10. oligotrophic peat bogs: *Sphagnum*, *Myrica*, *Cyperaceae*.

It is important for the paleogeographic reconstruction to correctly interpret the *Chenopodiaceae* in the paleobotanical record. As discussed in Bohncke (1984) a variety of habitats is suitable for species within the *Chenopodiaceae* family. The habitats that are associated with marine environments seem most applicable in this study: tidal mudflats of the eulittoral zone, salt-marshes of the supra-littoral zone and tidal litter zones (drift zones) near the mean high water level.

With respect to the salinity of the inundation water tidal litter zones embrace environments from polyhaline up to and including b-mesohaline, whilst salt-marshes and tidal mudflats occur in the poly- and eu-haline zone (salinity classification according to the Venice System, 1959).

The species associated with the *Chenopodiaceae* peaks can help to discriminate between the above mentioned possible environments. Salt-marshes and mudflats are characterized by obligate halophytes, while tidal litter zones are intermingled with a shore vegetation and bear species which are nitrophilous due to the decomposition of unwashed organic matter. Tidal litter zones are generally restricted to the contact zone between fresh water and brackish water and establish on damp soils or in temporarily inundated environments (Beefink, 1965).

Pollen types present at or around the levels of increased *Chenopodiaceae* values (in Beerse Blak, Ravels, Merksplas Strafinrichting, being the southeastern part of the area) are *Artemisia*, *Armeria*, *Polygonum persicaria* type, *Rubiaceae*, *Rumex hydrolapatum*-type, *Umbelliferae*, *Typhaceae*, *Lythrum*, *Lysimachia* and sometimes *Compositae tubelliflorae*-type. Similar pollen assemblages have been found in a detailed study on Dutch Holocene coastal environments (Bohncke, 1984) and have been interpreted as derived from phytocoenoses occurring in mesohaline conditions. *Atriplex* species establish in the understory of a vegetation on nitrogen rich ruderal drift zones. Its fresh water equivalent is the *Filipendulion* alliance. A closely associated phytocoenose may have been present at Ravels were *Chamaenerion*-type pollen and the nitrophilous *Urtica* occur in the transition from ruderal mesohaline to fresh water with increased *Alnus* values.

Comparison with data from actuo environments can further elucidate the type of depositional environment represented by the fossil pollen

assemblage. Surface samples from salt-marshes in the Baye de Mont St. Michel proved to be poor in pollen (Morzadec - Kerfourn pers. comm., 1985). Long periods of aeration throughout the year in combination with the rather coarse-grained sediments appear to result in a poor preservation. Pollen in tidal mudflats from the East Frisian Islands (northern Germany) is generally well represented although preservation is sometimes poor (Chowdhury, 1982). In conclusion we may assume that the levels with high Chenopodiaceae content reflect the transitional zones with species from fresh water and slightly brackish environments, intermingled with ruderal elements and approach phytocoenoses that are most closely associated with tidal litter zones from lagoonal and estuarine environments. This is supported by sedimentological analyses of the vertical intervals (Kasse, 1986; §3.3.4, §3.3.6), in which the Chenopodiaceae maxima are formed in an intermittent position in relation to the underlying subtidal sediments and the overlying fresh water alder swamps. Hence the Chenopodiaceae are classified in this study as tidal litter zone species: physiognomical group 2.

3.4.3 Turnhout and Woensdrecht Members

North-south transect (fig. 3.24):

1. Lower clastic unit:

The thick, lower clastic unit of the Turnhout Member, is represented by pollen zones: Beerse Blak 4.1 and 4.2, Merksplas Strafinrichting 4.1, Wortel 4.1, Meerle Slikgat 4.1, Galderse Meren 4.1 and Chaam Kapel 4.1 (fig. 3.24).

The bar diagrams reveal the following trends in the physiognomical groups. In the southernmost locations of the cross-section (Merksplas, Beerse Blak) the tidal litter zones (group 2) are well established. Furthermore, the herbaceous shore vegetation (group 4), carr vegetation, floodplain forest (group 5 and 6) and heath (group 9) are important in the pollen assemblage. Northwards at Meerle Slikgat groups 4, 5 and 6 are still significant. Group 9 is declining in favour of group 8 (coniferous forest). At the northernmost end of the transect (Galderse Meren and Chaam Kapel) this trend is even more evident whereas groups 5 and 6 have reached a minimum.

Interpretation

At the southern end of the transect (Merksplas and Blak) a marshy shore vegetation was present. Under the influence of tidal action organic debris was trapped here and tidal litter zones consisting among others, of Chenopodiaceae species established. Water depth must have been limited to allow the establishment of tidal litter zones, which develop near the upper limit of the MHW level. These litter zones apparently did not form a small rim bordering a brackish water marsh, but formed quite an extensive zone.

The relatively high values for groups 5 and 6 indicate the close presence of fresh water with carr vegetation and floodplain forest. Locally at Merksplas at the termination of this phase the herbaceous shore vegetation is represented by *Alisma plantago aquatica* and *Typha spp.*, while in shallow water *Azolla tegeliensis* and *Salvinia natans* thrived (fig. 3.25: 5.2 m). The high values for group 9 possibly derive from a heath that grew on the nearby outcropping Tertiary sandy substratum.

At Meerle Slikgat open water (3) and shore line vegetation became relatively more important and it is assumed that the average water depth increased northwards. Consequently, in the absence of temporarily emerging substratum, tidal litter zones (2) did not develop, resulting

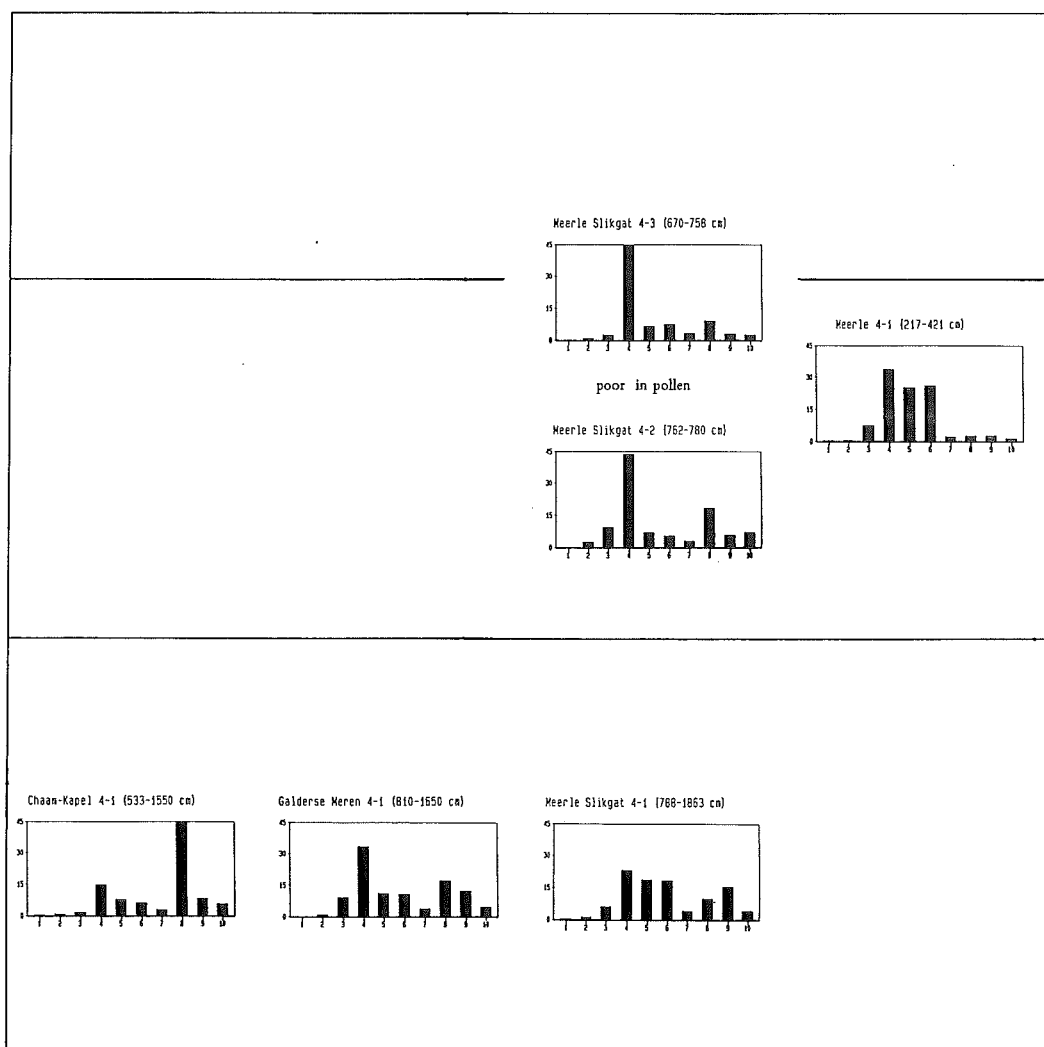
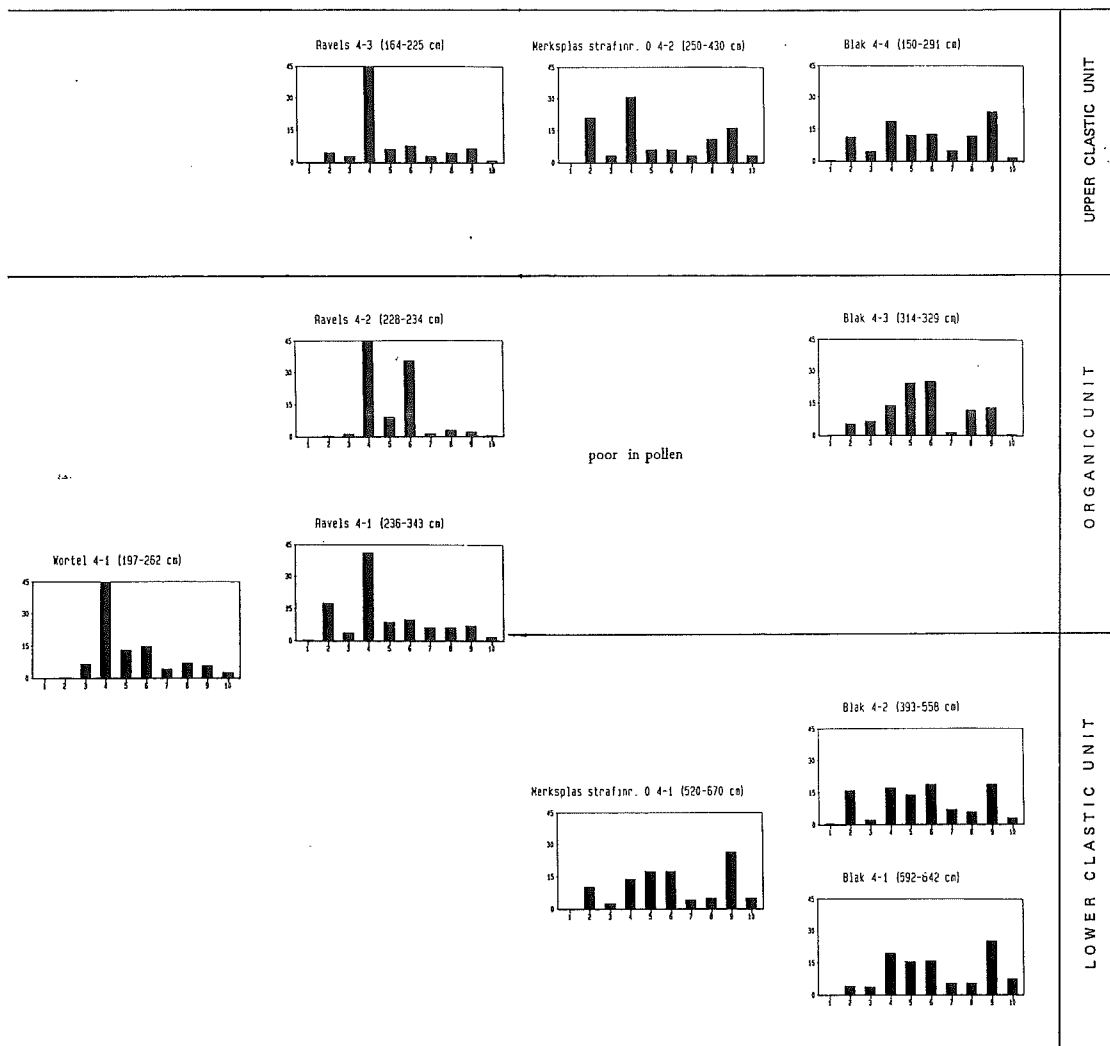


Fig. 3.24: North-south cross-section between Beerse Blak and Chaam Kapel. The bar diagrams with the physiognomical groups are arranged according to their lithostratigraphic position.

in the nearby absence of *Chenopodiaceae*. The northernmost sites (Chaam Kapel, Galderse Meren) appear to be further removed from the belt with floodplain forest (6) and carr vegetation (5). The increase in coniferous forest (8) seems to be an effect of selective enrichment with saccate pollen. Recent distribution patterns show an increase in *Pinus* pollen with increasing distance from the shore, especially in coarse-grained sediments (Chowdhury, 1982). Surface currents (Traverse and Ginsburg, 1966; Heusser and Balsam, 1977), high air current and resistance to destruction (Havinga, 1984) can all add to this phenomenon (cf. Chowdhury, 1982).

2. Organic unit

The organic unit in the Turnhout Member is registered at Beerse Blak (zone 4.3), Merksplas Strafinrichting (a sterile level), Wortel (zone 4.1), Meerle (zone 4.1) and Meerle Slikgat (zone 4.2, a sterile level and zone 4.3). The organic unit often consists of a humic clay or peat-bed, which has been studied in closer intervals than the preceding and



overlying clastic sediments. Hence a more detailed picture of the environmental changes can be obtained.

Palynologically the organic unit shows up by an increase in groups 5 and 6, carr vegetation and floodplain forest. Fresh open water (group 3) and herbaceous shore vegetation (4) are firmly present. Sometimes a level, sterile in pollen, remains.

Interpretation:

The sequence at Meerle Slikgat, the most northerly investigated site with a clear peaty horizon, offers the opportunity to study the organic level in detail, since both the onset (zone 4.2) and the termination of the peat formation (zone 4.3) are present. Moreover macro remain analysis of the levels involved are available. Part of the peat-layer was poor in pollen.

Zone 4.2 (onset of the peat formation) shows low percentages for most of the groups, except for group 4 (shore vegetation) and 8 (coniferous forest). Group 3 is relatively high, indicating the presence of fresh open water. This is confirmed in the macro remain record (fig. 3.26) by the presence of *Potamogeton* cf. *alpinus*, *Scirpus* cf. *lacustris*, *Alisma plantago aquatica*, *Batrachium*, *Hippuris*, *Mentha aquatica*, *Salvinia*, *Typha* and undetermined Compositae species. The paleoenvironment can be characterized as shallow, fresh water, with weak currents.

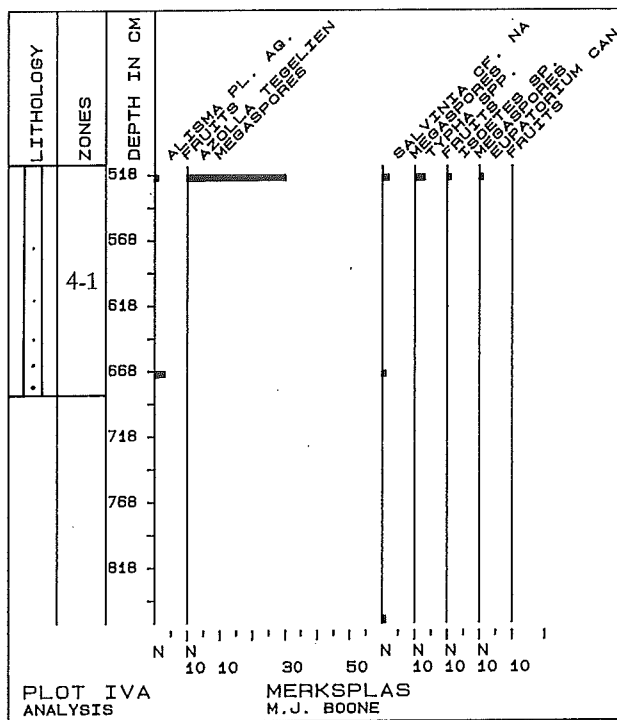


Fig. 3.25: Macro remain diagram of Merksplas Strafinrichting.

At a comparable level in site Meerle claypit the macro remains (fig. 3.27: 270-250 cm) indicate fresh, shallow standing water during this phase (*Sagittaria sagittifolia*, *Alisma plantago aquatica*, *Azolla tegeliensis*, *Typha* sp., *Salvinia* cf. *natans*). In the successive stage the open water area gradually declines and peat formation is initiated. Although the pollen is badly preserved the macro remains at this level in Meerle Slikgat (fig. 3.26: 7.58 m) reveal to some extent the species taking part in the peat formation. These are *Sparganium* sp., *Typha*, *Filipendula*, *Decodon* (Lythraceae), *Mentha*, *Carex rostrata* and other *Carex* sp., *Empetrum*, *Potentilla palustris* and *Menyanthes*. It is not unlikely that the peat at this level formed some

sort of floating mat (quaking bog): an unsuitable substratum for the establishment of trees.

In view of the environment indicated by the macro remains, corrosion of the pollen must have been a post-sedimentary process, which has taken place during a period of minimum water depth preceding the subsequent transgression phase with deposition of the upper clastic unit. The peat-bed or humic clay extends southwards and is correlated with Ravels 4.2, Meerle clay-pit 4.1 and Blak 4.3. Here the organic unit appears as a zone dominated by floodplain forest (6) and carr vegetation (5). At Merksplas Strafinrichting soil forming processes have resulted in a sterile level as well. Macro remain analyses at Ravels did not confirm the local presence of *Alnus* (fig. 3.28: 2.32 m). Instead *Typha* dominates together with *Decodon*, *Juncus* sp., *Mentha aquatica*, *Hypericum* cf. *maculatum* and some megaspores of *Azolla tegeliensis*.

The overlying transitional zone 4.3 at Meerle Slikgat shows low values for all physiognomical groups, except for group 4 (shore vegetation), which is mainly due to the overwhelming amount of Monolete spores. In the macro remains (fig. 3.26: 7.35 m) this zone 4.3 is characterized by the abundant presence of water ferns e.g. *Salvinia* cf. *natans* (megaspores), *Azolla tegeliensis* (megaspores and massulae) and *Elatine hydropiper* (seeds), besides seeds of *Typha* sp., *Mentha aquatica*, *Carex rostrata* and *Carex* sp., *Batrachium* and leaf echinae of *Stratiotes*. In contrast to Meerle Slikgat zone 4.2, zone 4.3 reflects stagnant, fresh water conditions. The difference between zone 4.2 and zone 4.3 can be explained by differences in current velocity. At the beginning of the peat formation (zone 4.2) brackish water was replaced by slowly running fresh water. Zone 4.3 was formed during the beginning of a transgression (upper clastic unit), when a rising local water level inhibited

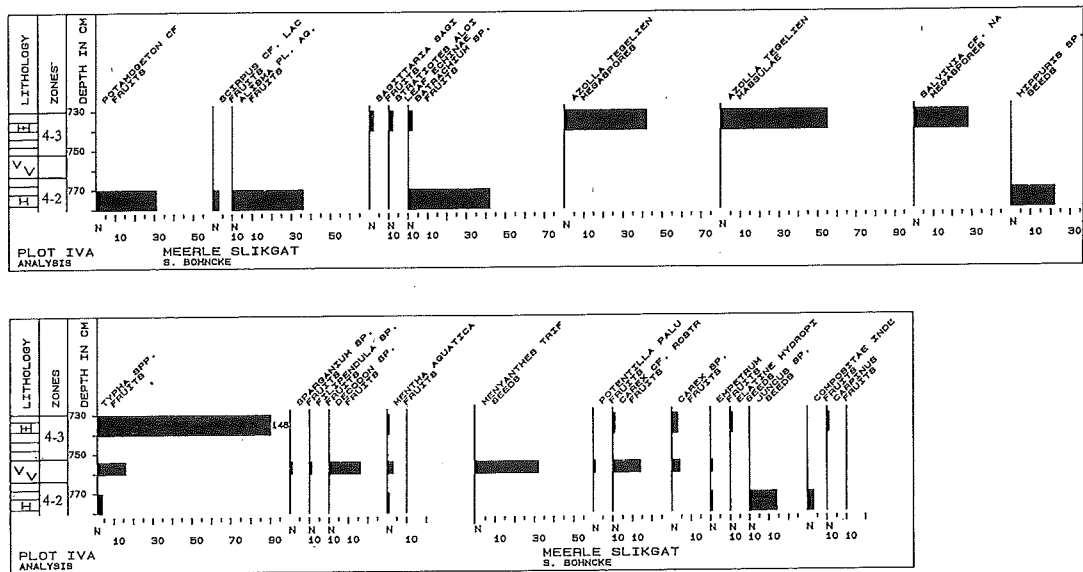


Fig. 3.26: Macro remain diagram of Meerle Slikgat.

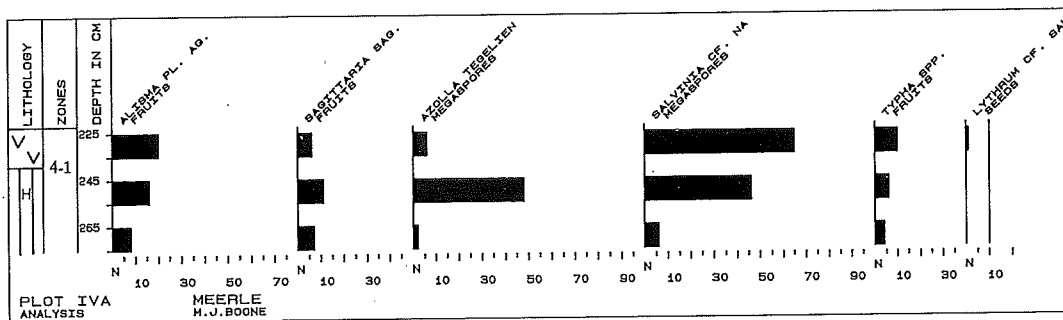


Fig. 3.27: Macro remain diagram of Meerle clay-pit.

the drainage and a stagnant, fresh water body built up, which subsequently became more brackish in the course of the transgression.

3. Upper clastic unit

This phase is present in bar diagram Blak 4.4, Ravels 4.3 and Merksplas Strafinrichting 4.2. The complexity of the lithological sequence more northwards does not allow a further correlation. Groups 2 and 4 (respectively tidal litter zones and herbaceous shore vegetation) are strongly represented. The amount of floodplain forest and carr vegetation (groups 5 and 6) is declining northwards (Merksplas 4.2) as does group 9 (heath).

Interpretation

At the time that the deposition of the upper clastic unit was at its maximum, tidal litter zones (group 2) reestablished at the southern shoreline of the intertidal basin (Blak 4.4, Merksplas 4.2 and to a lesser extent at Ravels 4.3). Tidal action resulted in a drift zone in

the shore vegetation (group 4), which established in the high inter-tidal region at about mean high water. With an increased distance from the shore (Ravels 4.3) the influence of floodplain forest, carr vegetation (resp. groups 6 and 5) and heath (group 9) is declining.

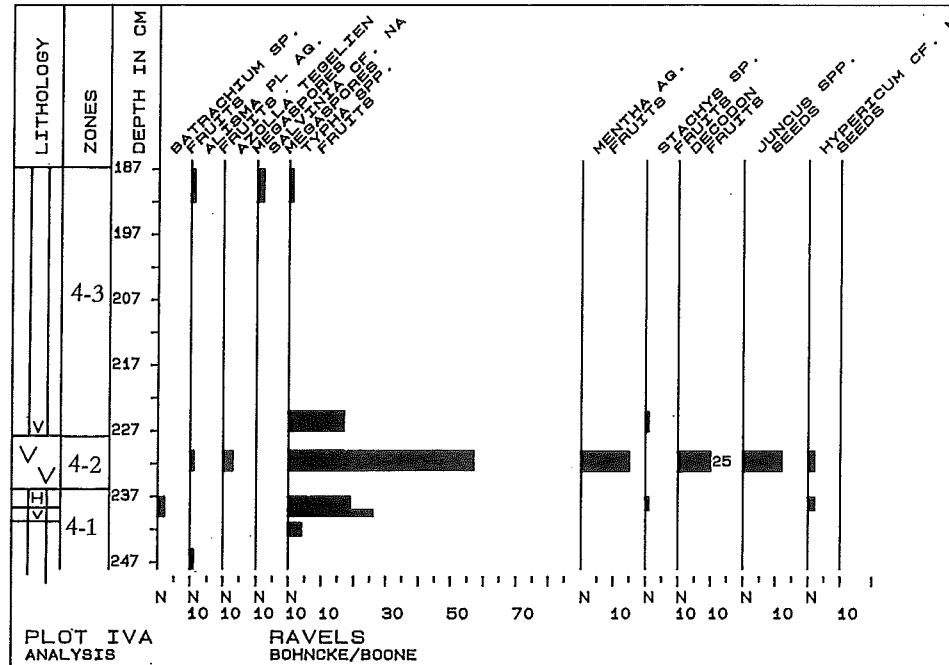


Fig. 3.28: Macro remain diagram of Ravels.

East-west transect (fig. 3.29)

Investigated sites: Appelenberg, Ravels, Zwart Water, Zwart Goor, Achtmaal, Wernhout Maalbergen and Kalmthoutse Hoek.

1. Lower clastic unit

The lower part of the Turnhout Member is represented by pollen zone Appelenberg 4.1, Zwart Water 4.1, Zwart Goor 4.1, Achtmaal 4.1 and 4.2, Wernhout Maalbergen 4.1 and Kalmthoutse Hoek 4.1 and 4.2.

The bar diagrams show the following trends: groups 4, 5 and 6 (resp. herbaceous shore vegetation, carr vegetation and floodplain forest) are well represented in all diagrams. From east to west the upland forest group 7 gradually declines. Open water species (group 3) and coniferous forest (group 8) show a concomitant increase.

Interpretation

The constant presence of the physiognomical groups 4, 5 and 6 possibly means that the east-west transect lies parallel to a paleo-vegetation zone consisting of a reed marsh associated type of vegetation (group 4) bordered by a carr and a belt with floodplain forest (groups 5 and 6). A westward decline in upland forest (group 7) presumably indicates that site Appelenberg in the southeast of the area lies most closely to this type of vegetation. More westward heath (group 9) is better represented (Kalmthoutse Hoek 4.2). The increase in coniferous forest (group 8) westward coincides with an increase in open water (group 3) and must be ascribed to the effects of water and air currents besides selective corrosion. The presence of open water is confirmed by the macro remain assemblage at Achtmaal (fig. 3.30).

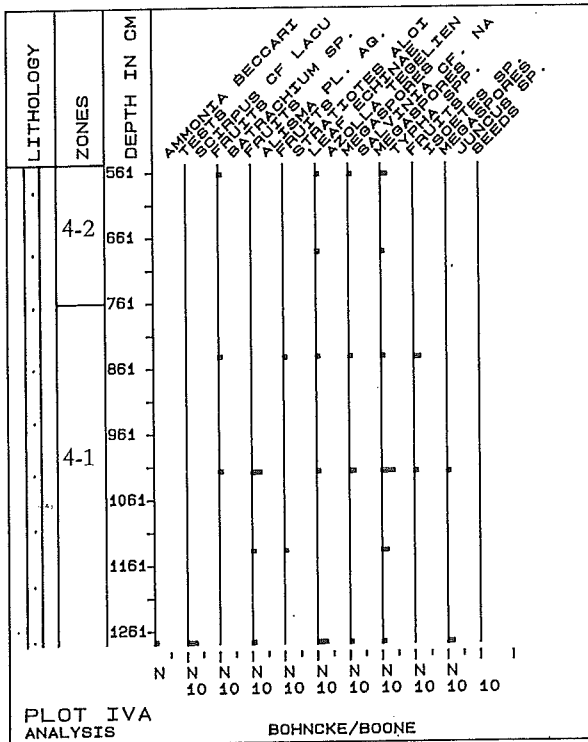


Fig. 3.30: Macro remain diagram of Achternaal.

2. Organic unit

This phase is registered in Appelenberg 4.2, Ravels 4.1 (transitional) and 4.2 and Zwart Water 4.2.

The major characteristics of this zone are the dominating presence of groups 4, 5 and 6 (resp. herbaceous shore vegetation, carr and flood-plain forest). All other physiognomical groups are only marginally present. The transitional phase at Ravels is characterized by groups 2 and 4 (tidal litter zones and herbaceous shore vegetation).

Interpretation

During the onset of the peat formation a belt with herbaceous shore vegetation intermingled with Chenopodiaceae (group 2) established at Ravels (zone 4.1). Possibly this belt moved northwards in the course of time and established at sites with temporarily emerging substratum. The fluvial

environment enlarged its influence to the west. Macro remain analyses proved bad preservation conditions at Ravels.

Nevertheless the following species were found present (fig. 3.28: 2.38 m): *Batrachium* sp., *Typha* sp., *Hypericum* cf. *maculatum* and *Stachys* cf. *palustris*. The sediments from this period have been deposited under anaerobic conditions, as shown by the high pyrite content in the clay, which oxidized after the sampling (development of the yellow mineral jarosite). This may indicate that during the deposition of zone 4.1 at Ravels the tidal range was limited.

The absence of group 2 at the maximum of the peat formation indicates a freshening of the depositional environment. Floodplain forest and carr vegetation spread over the area (Appelenberg 4.2, Ravels 4.2, Zwart Water 4.2). Macro remain analyses of the peat-bed at Ravels could not prove the local presence of *Alnus*, but its nearby occurrence is clear from the pollen record. The local high content of group 4 pollen (reed marsh associated vegetation) is confirmed by the overwhelming amount of *Typha* seeds (fig. 3.28: 2.32 m).

3. Upper clastic unit

5. Upper clastic unit
This phase is present in bar diagrams Appelenberg 4.3, Ravels 4.3 and Zwart Water 4.3.

Paleobotanical data are restricted to the southeastern part of the area. Group 4, the herbaceous shore vegetation, declines at Appelenberg but remains firmly present at Zwart Water 4.3 and dominates at Ravels 4.3. Tidal litter zones (group 2) are weakly present. Groups 8 (coniferous forest) and 9 (heath) increase somewhat.

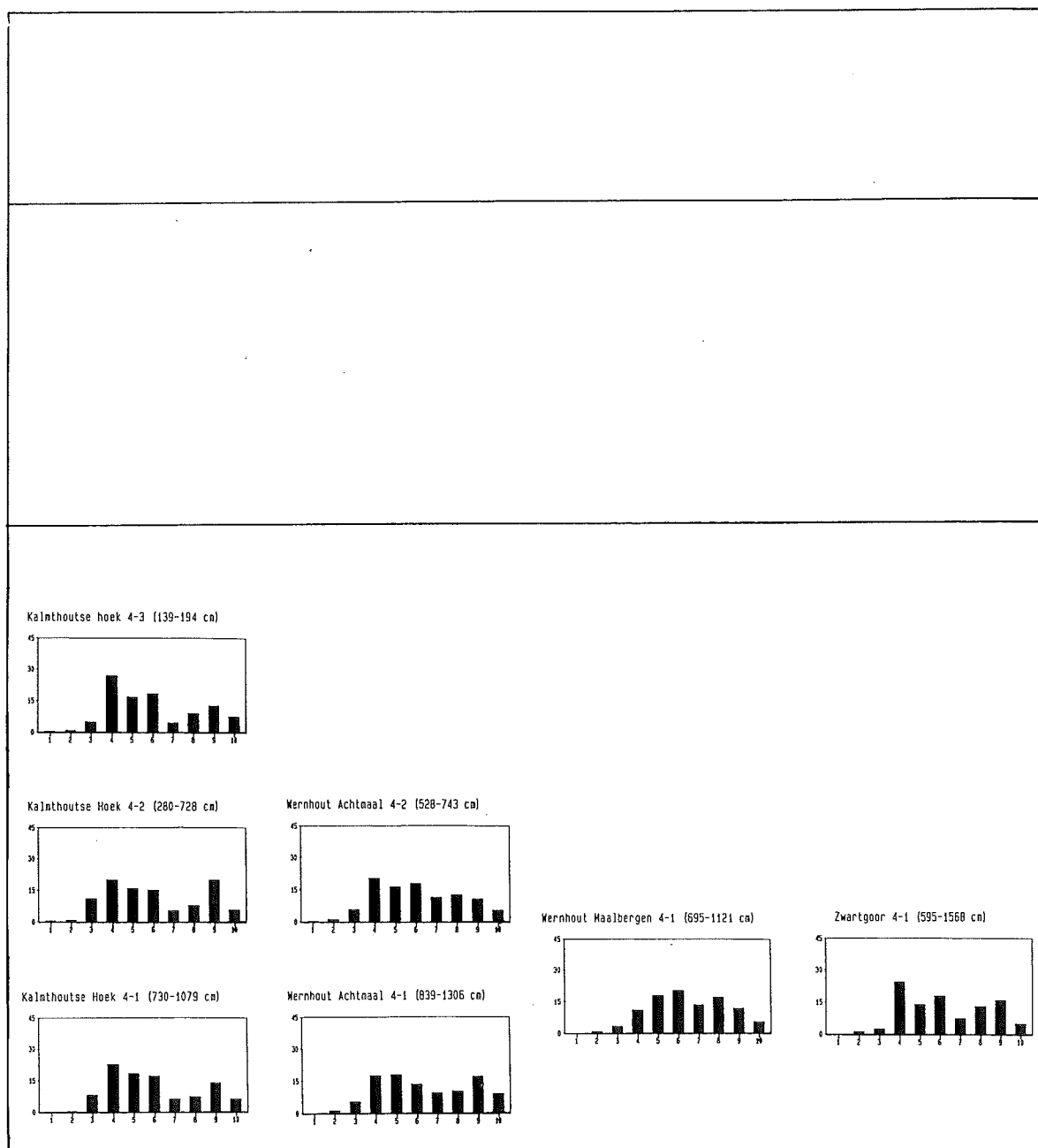
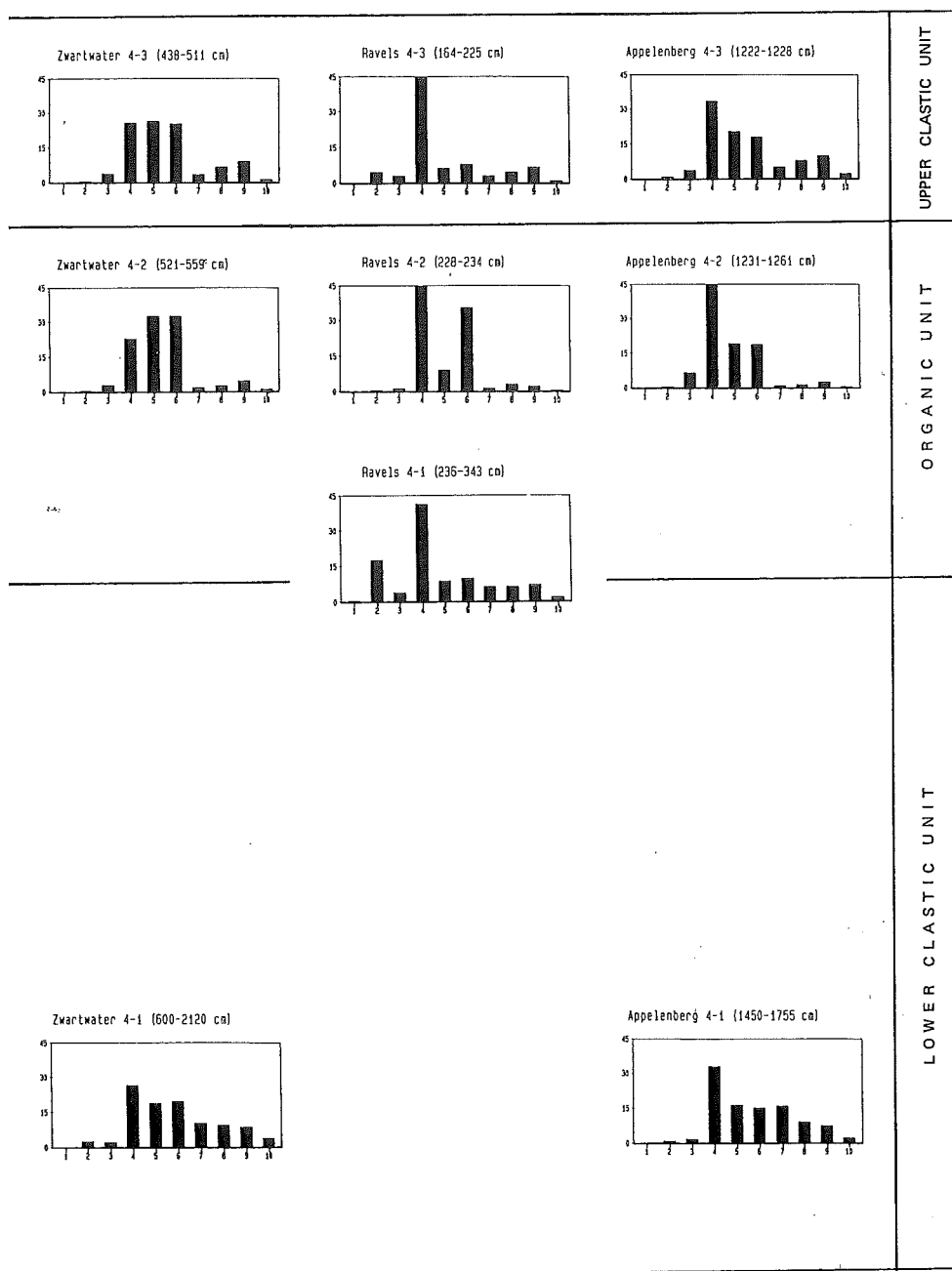


Fig. 3.29: East-west cross-section between Appelenberg and Kalmthoutse Hoek. The bar diagrams are arranged according to their lithostratigraphic position.

Interpretation

Only Ravels contains the transition from the organic unit to the overlying clastic unit. The transitional zone shows a drowning of the alder swamp forest, a short phase with strong increase of Gramineae (group 4) after which tidal litter zones reestablish (group 2: Chenopodiaceae). In the macro remains *Typha* seeds are present (fig. 3.28: 2.25 m). *Stachys cf. palustris* indicates, that the initial drowning occurred under almost fresh water conditions. The pollen record even reveals the presence of *Myriophyllum sp.*

The influence of this transgression is hardly felt at Appelenberg.



Group 2 is found in very low values. At Zwart Water open water conditions increase somewhat (group 3) permitting a more regional registration of the pollen rain (increase of groups 7 and 8).

North - south transect in the western part of the area between Ossendrecht and Wouwse Plantage (fig. 3.31)

The following sites have been taken into consideration: Ossendrecht, KW7, WW9 (Korteven) and Wouwse Plantage.

1. lower clastic unit

Bar diagrams Ossendrecht 4.1, 4.2; Wouwse Plantage 4.1.

Main characteristics: The southern end of the transect at Ossendrecht is dominated by heath (group 9). The groups 5 and 6, carr vegetation

and floodplain forest, are relatively well represented at both sites. Group 4, the marshy shore vegetation, is important. Tidal litter zones (group 2) are mainly present at Ossendrecht.

Interpretation

At Ossendrecht the two bar diagrams show a development from a nearby marshy fringe vegetation (group 4) with tidal litter zones (group 2) towards an increased presence of floodplain forest (group 5 and 6). Apparently the tidal influence decreased and fresh water river environments developed.

The same trend, to some extent, is visible in the macro remains (fig. 3.32). The lower zone contains *Puccinellia* fruits, indicating the close presence of supra-tidal salt-marshes. It may not be excluded that *Puccinellia* invaded the reed marshes of the mesohaline zone (Gillham, 1957). Zone 4.2 at Ossendrecht contains macro remains of *Stratiotes* (leaf echinae) and *Alisma*, indicating the presence of shallow, standing, fresh water.

The high Ericaceae values in the bar diagrams (group 9) may be related to the close presence of the outcropping Tertiary substratum at the southern end of the transect. Wouwse Plantage, at the northern end of the transect, shows relatively more open water (group 3) and, associated with this, more coniferous forest (group 8) due to long distance transport. Also the litter zones (group 2) at this locality are less well represented due to the absence of temporarily emerging substratum.

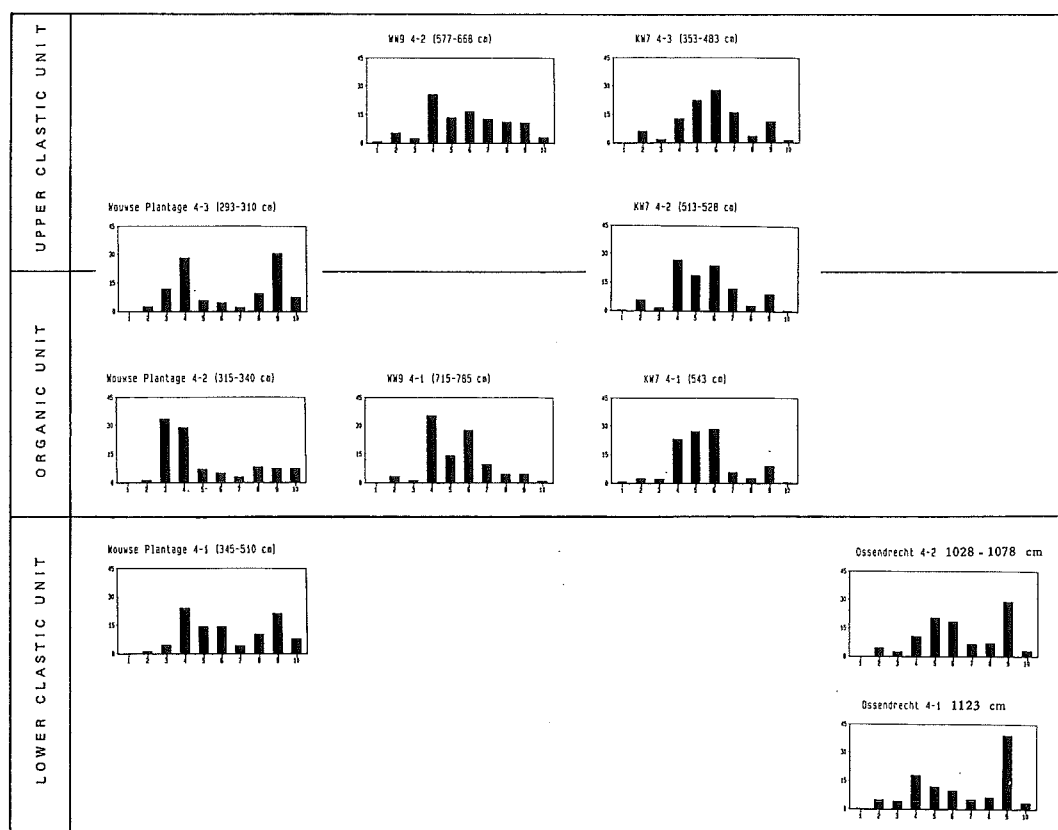


Fig. 3.31: North-south cross-section in the western part of the investigated area between Ossendrecht and Wouwse Plantage.

2. Organic unit

This unit is present in bar diagrams Wouwse Plantage 4.2, KW7-4.1 and WW9-4.1.

The main characteristics of this phase are the low presence of group 2 (tidal litter zones) and a northward shift from a belt dominated by groups 4 (herbaceous shore vegetation), 5 (carr vegetation) and 6 (floodplain forest) via an intermediate form to a belt with open, fresh water with herbaceous shore vegetation.

Interpretation

From south (KW7) to north (Wouwse Plantage) there is a transition from a floodplain forest (6) with carr vegetation (5) via a reed marsh dominated vegetation (4) with some floodplain forest elements (6) to an environment dominated by open water (3) bordered by herbaceous shore vegetation (4).

The open water environment contains macro remains of the following species (fig. 3.33, 3.34, 3.35): *Typha*, *Alisma plantago aquatica*, *Batrachium*, waterferns like *Callitriche* sp. and *Azolla tegeliensis*, *Juncus* sp. and *J. effusus*. In Korteven (WW9) badly preserved Chenopodiaceae seeds were found, which could not be identified to the species level.

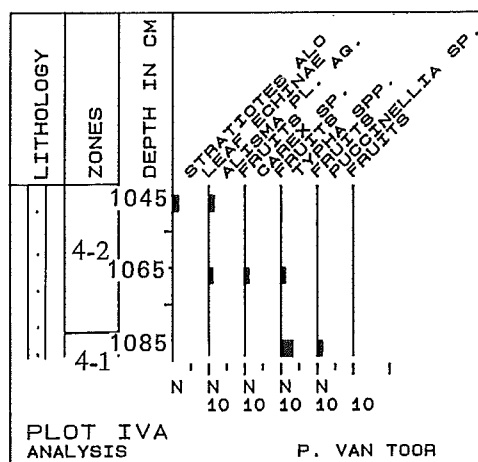


Fig. 3.32: Macro remain diagram of Ossendrecht.

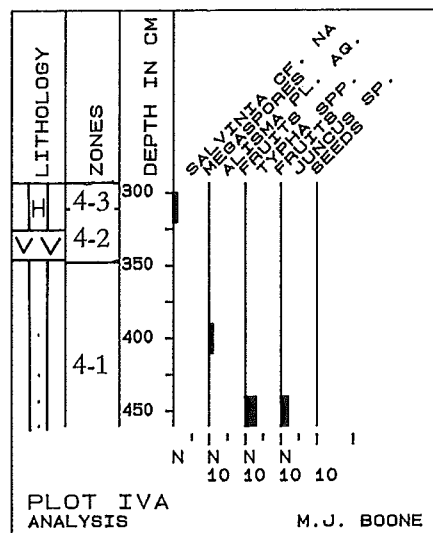


Fig. 3.33: Macro remain diagram of Wouwse Plantage.

3. The transition to the upper clastic unit

The transition to the overlying clastic phase is registered in KW7-4.2 and Wouwse Plantage 4.3, where the Chenopodiaceae content increases (group 2) and a herbaceous shore vegetation (group 4) with Gramineae and *Typha angustifolia* form the local elements. Alder swamp forest (group 5 and 6) is relatively low in the northern part of the cross-section but well represented in KW7-4.2, as is the upland forest (group 7). In Wouwse Plantage besides Ericaceae (group 9) the long distance transported pollen of the coniferous forest remain important.

Macro remains at KW7 (zone 4.2)(fig. 3.34) indicate the strong presence of open, standing water (*Potamogeton*, *Azolla tegeliensis*, *Typha*) and associated fringe vegetation (*Lycopus*, Cyperaceae, Gramineae). The presence of *Ammonia beccarii* points to periodical marine inundations.

fruits of *Puccinellia*, *Triglochin* and the foraminifer *Ammonia beccarii* (fig. 3.34). Also one fruit of *Phragmites australis* has been encountered, a species which was expected to be more frequently present in the macro remains. Other species present in the macro remains are *Scirpus* sp., *Callitriche*, *Isoetes*, *Carex* sectie *Acutae*, *Typha*, *Juncus* sp. and *Sphagnum* leaf remains. WW9-4.2 contains *Typha* seeds (fig. 3.35). In conclusion the macro fossil assemblage represents a mixture from various environments. Moreover, the bar diagrams reveal that KW7 is located more closely to a belt with floodplain forest (group 6) and upland forest (group 7) in the south, than WW9.

3.4.4 Conclusions (fig. 3.36)

Towards the termination of the deposition of the lower clastic unit, tidal litter zones established in the understory of the upper zone of the intertidal marsh (fig. 3.36, phase a and b). These *Chenopodiaceae* rich tidal litter zones were located at the SE part of the investigated area. Northwards of the line Ravels-Merksplas Strafinrichting tidal action did not result in temporarily emerging substratum and tidal litter zones were absent. A belt with herbaceous marsh vegetation (predominantly *Typha*) bordering on pools was present.

In the western part of the area, at Ossendrecht, an intertidal marsh consisting of *Typha* intermingled with *Puccinellia* was present.

Within the onset of the peat formation, a freshening of the water took place allowing *Potamogeton*, *Hippuris*, *Batrachium*, *Salvinia* and *Alisma plantago aquatica* to establish in the shallow pools (Meerle Slikgat and Meerle) (fig. 3.36, phase c). Westwards *Stratiotes* and *Alisma* proved to be present (Ossendrecht).

At the maximum of the peat formation *Alnus* (groups 5 and 6) increased in the pollen record. Although macro remain analyses are very incomplete the analysed organic levels (Ravels, Meerle Slikgat, Meerle) never revealed macrobotanical remains of *Alnus*. Studies on the actual pollen deposition in open systems with an inflow and an outflow (Peck, 1973; Bonny, 1976) showed a considerable supply of stream-borne pollen to the yearly pollen influx into lakes. For marine environments the highest pollen concentrations were found opposite to river mouths (Muller, 1959; Heusser and Balsam, 1977). It appears from the studies by Peck (1973) and Bonny (1976) that the water-borne component can attain values up to 90-97%, whereas the aerial deposition varies between 10 and 3% of the total. Moreover, amongst the pollen-types that show a differential input, *Alnus* occurs in significantly larger proportions in the stream-borne component (Bonny, 1976).

It is concluded that the increase of *Alnus* in the pollen diagrams results from an extensive zone with alder floodplain forest that established southeast of the investigated area. River systems running through this zone with alder floodplain forest are responsible for the large proportion of stream-borne *Alnus* pollen, deposited during the peat formation. Fruits and bud scales of *Alnus* show a different hydrodynamical behaviour and may have been trapped in the abundantly present intertidal marshes to the south and southeast. The organic level itself is characterized by an herbaceous vegetation intermingled with pools with fresh, standing water. These pools were vegetated by species like *Azolla tegeliensis*, *Salvinia* cf. *natans*, *Alisma plantago aquatica*, *Sagittaria sagittifolia* and *Menyanthes* (fig. 3.36, phase d). The herbaceous marsh consisted of *Typha* spp. (dominant species), *Sparganium*,

- Fig. 3.36: Tentative reconstruction of the paleobotanical environment in a north-south cross-section between Beerse Blak and Chaam Kapel. The following stages are depicted:
- termination of the lower clastic unit.
 - transition to the organic unit.
 - and d. maximal development of the organic unit.
 - transition to the overlying clastic unit.
 - development of the upper clastic unit.

Mentha aquatica, *Potentilla palustris*, *Carex rostrata*, *Carex* sect. *Acutae*, *Carex* spp., *Filipendula*, *Decodon* and *Hypericum* cf. *maculatum*. At the western border of the area (Korteven (WW9), KW7) *Callitriche* and *Alisma plantago aquatica* are found besides *Typha* and *Juncus* seeds. With the onset of the deposition of the upper clastic unit the area with fresh, open water increased (fig. 3.36, phase e). In the west (KW7) *Potamogeton* and *Azolla tegeliensis* established. At Meerle Slikgat (in the east) these species are accompanied by *Batrachium*, *Stratiotes*, *Salvinia* cf. *natans* and *Elatine hydropiper*. The pools were bordered by *Typha* spp. (fig. 3.36, phase e). In the course of the transgression tidal litter zones reestablished in the SE part of the area (Ravels, Merksplas, Blak) probably under the influence of an increase in tidal range (fig. 3.36, phase f).

In the western part of the area (KW7) the intertidal marsh became invaded by *Triglochin*, *Puccinellia*, *Scirpus* cf. *lacustris* and *Phragmites australis*. Tests of *Ammonia beccarii* occur in the sediment. Apparently the intertidal marsh here lay within the then existing mesohaline zone.

3.5 Additional results concerning the depositional environments

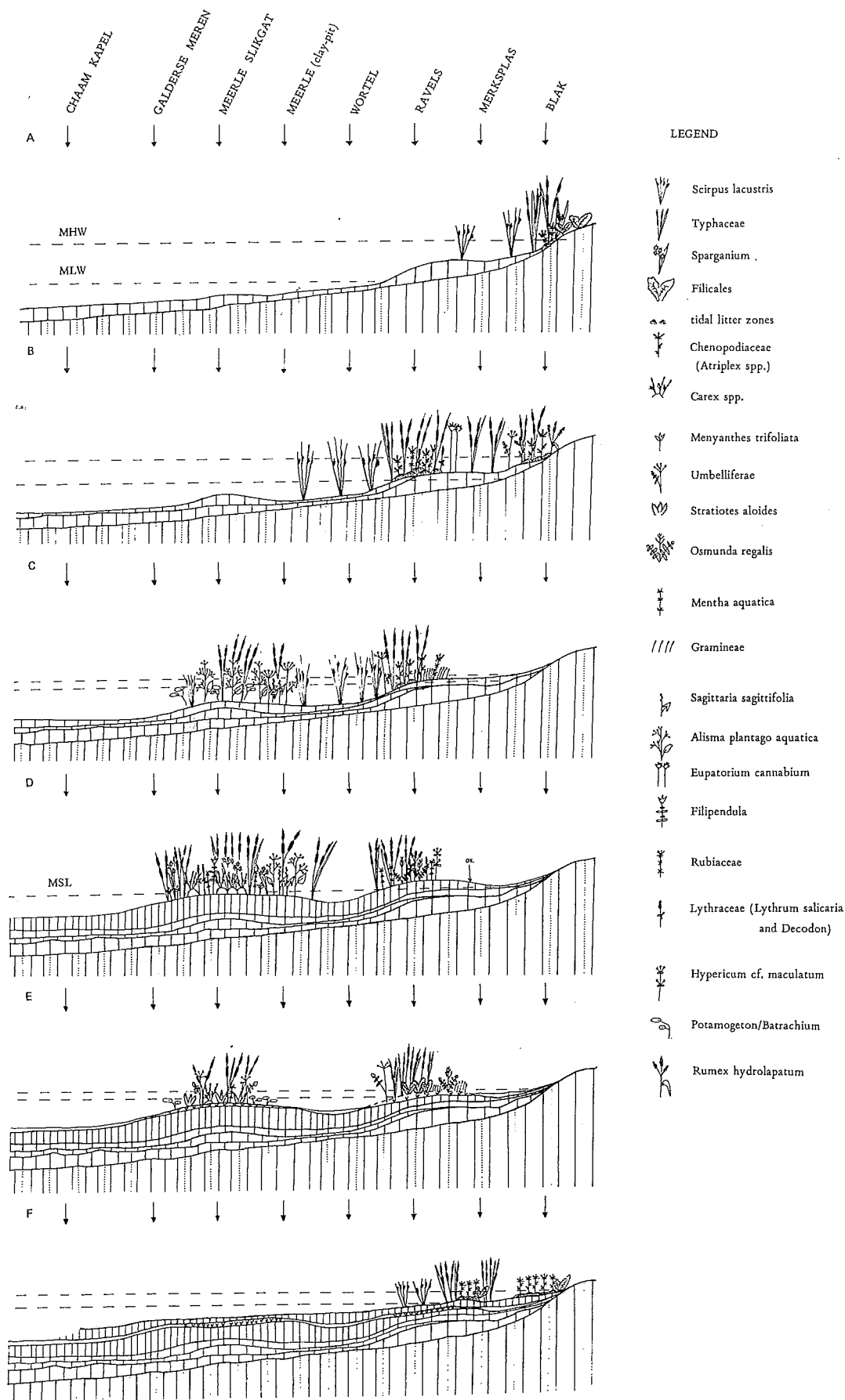
3.5.1 Grain-size analysis

Grain-size characteristics have been used previously to define lithological units and sedimentary environments in the study area (Geys, 1975). The environmental conclusions based on grain-size parameters as presented by Geys are different from the results based on the interpretation of sedimentary structures in this study (§3.3). For this reason the sediments in the study area were first interpreted according to their lithostratigraphic position and sedimentary structures. Then the results of the grain-size analysis were plotted in diagrams in order to see whether the defined groups showed a certain coherence in grain-size parameters. The results are presented in the figures 3.37, 3.38 and 3.39.

<2µm/<16µm ratio and silt content:

The <2µm/<16µm ratio and silt content have been used successfully in the past to differentiate between fluvatile, marine and estuarine clay deposits (Zuur, 1936; Wiggers, 1955; Zonneveld, 1960; Van Straaten, 1964; Poelman, 1965).

Marine (tidal flat and salt-marsh) deposits were characterized by <2µm/<16µm x 100 values between 65 and 70 (Zuur, 1936; Zonneveld, 1960). Fluvatile deposits showed somewhat lower <2µm/<16µm values ranging between 55 and 65 (Zonneveld, 1960; Poelman, 1965). The fresh water tidal deposits of the Biesbos area revealed, however, much lower <2µm/<16µm values, between 40 and 60 (Zonneveld, 1960; Poelman, 1965).



Extreme, low $<2\mu\text{m}/<16\mu\text{m}$ values (35-42) were found in fresh to slightly brackish lagoonal deposits (Wiggers, 1955: "sloef" deposits). Van Voorthuysen (1957, p. 51) pointed already to the similarity of the low $<2\mu\text{m}/<16\mu\text{m}$ values in the "Halsteren Beds" (our Woensdrecht Member) and in the "sloef" deposits.

Poelman (1965) compared the (coarse) silt content (16-53 μm) of fluvial and fresh water estuarine deposits in the Land van Heusden en Altena (Central Netherlands). The fluviatile deposits commonly contain less than 35% coarse silt, while the estuarine deposits contain more than 35% coarse silt in 66% of the samples (N=219).

The low $<2\mu\text{m}/<16\mu\text{m}$ values and high coarse silt content in fresh to brackish water tidal deposits was explained by peptisation of marine coagulated clay-flakes (Wiggers, 1955; Van Straaten, 1964). When a marine clay/silt/fine sand flake is transported from a salt into a brackish or fresh water environment, the change in salinity causes peptisation of the flake. The separate constituents of the flake are transported further and settle with current velocities corresponding to the particle size of the constituents. Clay-particles smaller than 2 μm only settle in the most quiet environments. Since silt has already settled previously, the $<2\mu\text{m}/<16\mu\text{m}$ values increase in such sheltered, landward environments (Wiggers, 1955).

The fine-grained samples from clay- and silt-beds have been analysed with the pipette method and plotted according to their lutum ($<2\mu\text{m}$) and lutum-fine silt ($<16\mu\text{m}$) ratio (fig. 3.37) and to their coarse silt (16-53 μm) content (fig. 3.38).

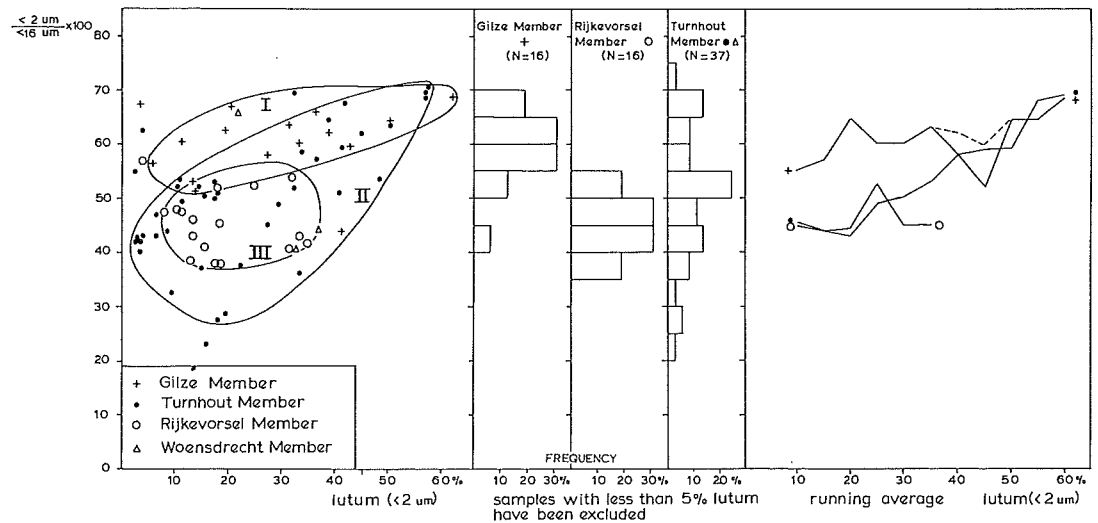


Fig. 3.37: Lutum/lutum-fine silt ratio of different lithostratigraphic units.

The $<2\mu\text{m}/<16\mu\text{m}$ ratio varies between 23 and 70 (fig. 3.37). $<2\mu\text{m}/<16\mu\text{m}$ values increase with higher lutum content. Three populations have been distinguished, corresponding to the Gilze, Turnhout and Rijkvorsel Members respectively.

Population I (Gilze Member) is characterized by $<2\mu\text{m}/<16\mu\text{m}$ values between 55 and 65. Population II (Turnhout Member) reveals a very low $<2\mu\text{m}/<16\mu\text{m}$ ratio (45) when the lutum content is low (10-25%) and is clearly different from population I. However, with lutum content increasing the $<2\mu\text{m}/<16\mu\text{m}$ ratio of population II increases to values

which are comparable to the $<2\mu\text{m}/<16\mu\text{m}$ values of population I (circ. 70). Population III (Rijkevorsel Member) is a subpopulation of group II, with $<2\mu\text{m}/<16\mu\text{m}$ values between 40 and 50.

The (coarse) silt content (16-53 μm) of the samples (fig. 3.38) varies between 5 and 80%. The three populations show much overlap. Population I (Gilze Member) has a relatively low silt content (less than 40%). Population II (Turnhout Member) is characterized in general by a very high coarse silt content (40-75%) when lutum values are below 20%. Population III (Rijkevorsel Member) shows intermediate values between 40-60%, when lutum content is lower than 20%.

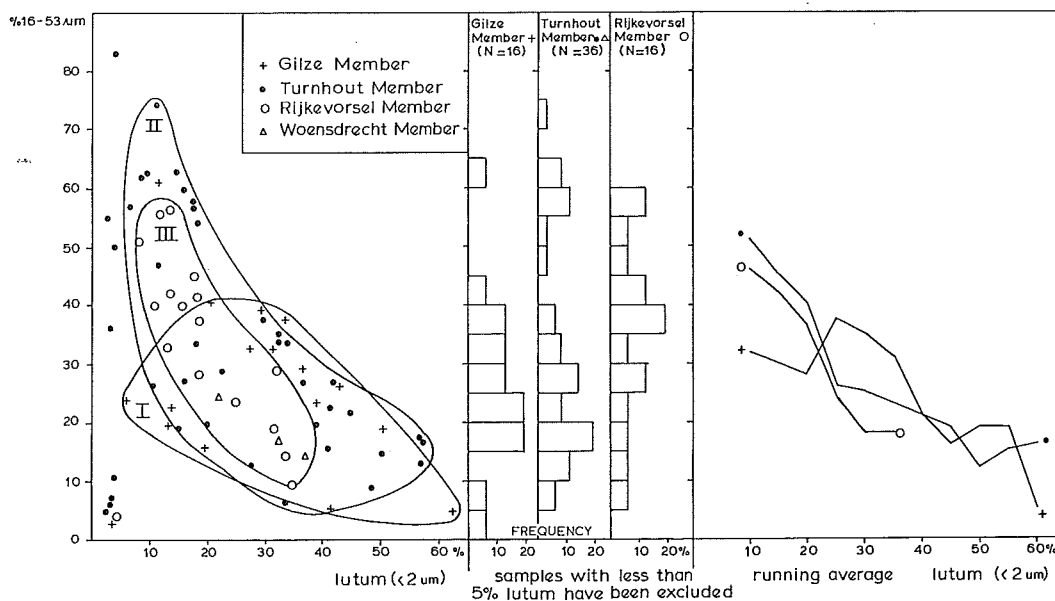


Fig. 3.38: Coarse silt content of different lithostratigraphic units.

Comparison of the $<2\mu\text{m}/<16\mu\text{m}$ values and coarse silt content of the samples in the study area with former investigations leads to the following conclusions:

1. The high $<2\mu\text{m}/<16\mu\text{m}$ ratio (55-65) and low coarse silt content (less than 40%) of the Gilze Member (population I) are comparable with sub-recent fluvial sediments (Poelman, 1965).
2. When lutum content is low, the low $<2\mu\text{m}/<16\mu\text{m}$ ratio (40-55) and high coarse silt content (more than 40%) in both the Turnhout (population II) and Rijkevorsel Members (population III) are comparable to sub-recent, fresh water, tidal deposits in the Biesbos area (Zonneveld, 1960). The high ratio (60-70) in samples with high lutum content (more than 45%) is not interpreted as an indication of salt water deposition. It reflects deposition of peptized suspended clay in the most sheltered, landward, fresh to brackish water, tidal environments (e.g. tidal litter zone).
3. The $<2\mu\text{m}/<16\mu\text{m}$ ratio (40-55) of the tidal deposits of the Turnhout and Rijkevorsel Members are higher than the $<2\mu\text{m}/<16\mu\text{m}$ ratio (35-42) in fresh to brackish water, lagoonal deposits ("sloef") (Wiggers, 1955).
4. The low $<2\mu\text{m}/<16\mu\text{m}$ values and the high coarse silt content in the brackish to fresh water, tidal deposits of the Turnhout and Rijkevorsel Members, is explained by peptisation of coagulated flakes during their landward transport from salt marine to brackish and fresh water tidal environments (Van Straaten, 1964).

Mean, standard deviation and skewness:

The coarser grained samples from sand-beds have been analysed by the dry sieving method and plotted according to their mean values, standard deviation (sorting) and skewness (fig. 3.39). The fractions coarser than 53 μm (4.25 phi) have been sieved in quarter phi intervals. The grain-size classes finer than 53 μm have not been investigated separately. The skewness and standard deviation have been calculated for a grain-size distribution above 2 μm (9 phi).

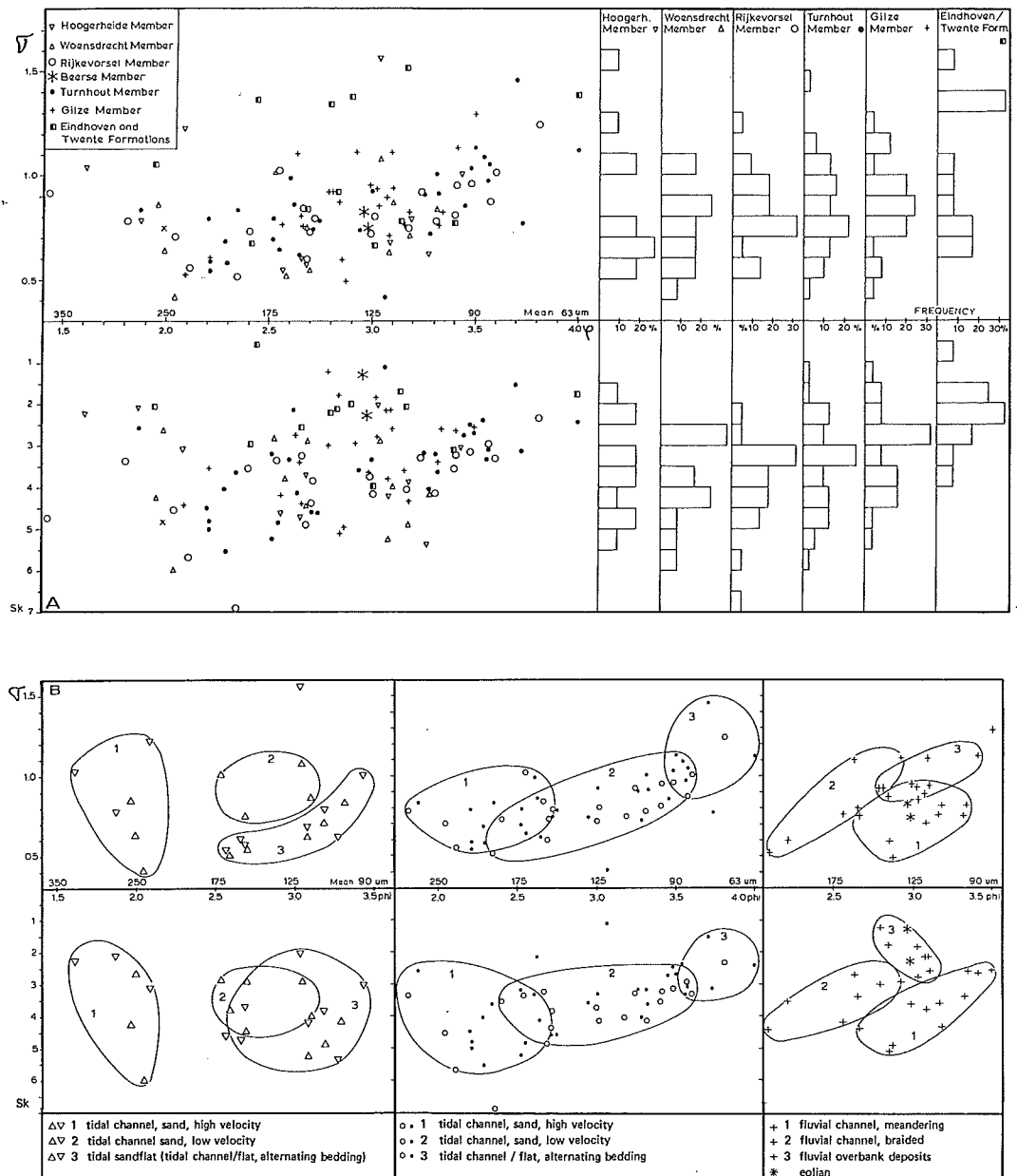


Fig. 3.39: Mean, skewness and standard deviation of coarse-grained samples in connection with the depositional environments.

Some general trends can be seen in the diagram (fig. 3.39A: left side):

1. The standard deviation increases (poorer sorting) with decreasing grain-size, which can be explained by a mixture of sediment in the fine sand samples (e.g. alternations of sand-silt-clay).

2. The generally positive skewness tends to zero with decreasing grain-size, because a fine-grained tail (positive skewness) is more important in coarser grained samples, than in finer grained samples.
3. The various members and formations do not form distinct populations, according to their grain-size parameters.

The frequency distributions of the skewness and the standard deviation of the individual members show that (fig. 3.39A: right side):

1. Sorting is good (standard deviation: 0.75) and skewness is highly positive ($Sk = 3.25$) for the tidal deposits of the Hoogerheide, Woensdrecht, Rijkevorsel and Turnhout Members.
2. Sorting is slightly poorer ($\sigma = 0.85$) and the skewness is slightly lower ($Sk = 2.75$) in the fluvial Gilze Member.
3. Sorting is poor (standard deviation: 1.35) and skewness is low ($Sk = 2.25$) in the Eindhoven and Twente Formations, which were formed by small, fluvial channels and surficial runoff.

In order to characterize the sedimentary sub-environments of the members the grain-size characteristics were plotted for each member or genetically related members (fig. 3.39B). The following conclusions can be drawn:

1. The sub-environments in most of the members are characterized more by their mean grain-size values, than by their standard deviation and skewness. However, some exceptions occur:
 - The sandflat deposits of the Hoogerheide and Woensdrecht Members are generally better sorted and have a higher skewness than channel deposits of equal grain-size.
 - The tidal channel/mixed flat deposits of the Rijkevorsel and Turnhout Members have a relatively poor sorting, because of their alternating sand-clay bedding.
 - The fluvial overbank deposits of the Gilze Member have a poorer sorting and especially a lower skewness, than channel sediments with a comparable grain-size.
2. The sediments of sub-environments in the Hoogerheide and Woensdrecht Member are, in general, coarser grained than the sediments of corresponding sub-environments of the Turnhout and Rijkevorsel Members. This difference has been explained previously (chapter 3) by the more seaward location of the Hoogerheide and Woensdrecht Members in comparison with the more sheltered, landward position of the tidal environments of the Turnhout and Rijkevorsel Members.

Finally, some general conclusions can be formulated, based on the grain-size analysis of 185 samples:

1. The $<2\mu m / <16\mu m$ ratio and coarse silt content enable differentiation between clay-beds of a fluvial and brackish to fresh water tidal origin, especially when the lutum content of the samples is low (between 5 and 45%).
2. The skewness and standard deviation are in general inappropriate to distinguish environments, although sandflat, fluvial overbank and local surficial runoff deposits seem to be characterized by specific skewness and/or sigma values.
3. The mean grain-size values of the samples is the most important factor to separate sub-environments.
4. The combination of sedimentary structures, the mean grain-size, the skewness and the standard deviation gives a good characteristic of the sub-environments.

3.5.2 Clay-mineralogy

Clay-mineralogical data from the Early-Pleistocene deposits in Noord-Brabant are scarce. Breeuwsma and Zwijnen (1984) investigated the clay-mineralogical composition of the Tegelen, Sterksel and Veghel Formations in Noord-Brabant. The Tegelen Formation is dominated by illite and smectite clay-minerals. The Sterksel and Veghel Formations are also dominated by illite, with chlorite and illite-chlorite content higher than in the Tegelen Formation. According to Breeuwsma and Zwijnen (1984), the differences in clay-mineralogical composition between the formations probably reflect different sediment sources: the Tegelen sediment was supplied by the Rhine, whereas the Sterksel and Veghel deposits were supplied by the Meuse. The supposed Meuse origin of the Sterksel Formation is only partly confirmed by the gravel and heavy mineral analysis (chapter 5).

3.5.3 Cation exchange capacity

According to Breeuwsma (1985) cation exchange capacity (CEC) can be related to the depositional environment. The CEC in Holocene river clay was found to be higher than in marine clay. In order to ascertain whether comparable differences are also present in Early-Pleistocene deposits in the study area, 8 samples from various members have been analysed. The results are presented in table 3.1 (values between brackets are percentages).

Table 3.1: Cation exchange capacity of Early-Pleistocene deposits in Noord-Brabant.

Location	Depth (in m)	Member	in meq/100 gr dry soil				Total	Ca in Mg extr. corr.	CEC	Environment based on sedimentary structures
			K	Na	Ca	Mg				
Bavel	10.1	Bavel	0.100 (0.9)	0.118 (1.0)	10.16 (89.0)	1.03 (9.0)	11.41	0.82	0.95	fluviatile +++
Gilze	3.65	Gilze	0.178 (2.2)	0.199 (2.4)	3.97 (48.8)	3.78 (46.5)	8.13	1.32	7.56	fluviatile -
Ravels	2.50	Turnhout	0.083	0.034	4.17	-	-	2.88	1.50	tidal litter zone -
Meerle	9.42	Turnhout	0.166 (2.7)	0.174 (2.8)	4.22 (69.0)	1.56 (25.5)	6.12	1.24	5.24	fresh-brackish -
Slikgat	8.12	Turnhout	0.380 (2.3)	0.171 (1.0)	12.62 (75.7)	3.51 (21.0)	16.68	1.43	14.34	tidal
Achtmaal			0.159 (1.6)	0.076 (0.8)	8.02 (79.2)	1.86 (18.4)	10.12	0.55	8.29	fresh-brackish +
Meerle	21.3	Rijkevorsel	0.135 (2.2)	0.118 (1.9)	3.15 (50.6)	2.82 (45.3)	6.22	1.20	4.55	brackish tidal -
Slikgat	19.4	Rijkevorsel	0.132 (1.7)	0.075 (1.0)	6.64 (87.5)	0.74 (9.7)	7.59	0.81	6.89	tidal
Achtmaal										brackish tidal ++
Zwart Goor	19.4	Rijkevorsel								

The CEC values for Bavel and Ravels are probably erroneous, since they are lower than the Ca content. The CEC of the rest of the samples is highly variable. The samples from fluviatile, fresh water tidal and brackish tidal environments do not form distinct CEC groups.

Calcareous (+), fluviatile sediment (Bavel) and calcareous, brackish tidal sediment (Zwart Goor) have a comparable high Ca and low Mg content. Non-calcareous (-), fluviatile (Gilze) and brackish tidal (Achtmaal: 19.4 m) deposits are characterized by a high Mg and relatively low Ca content. Samples with intermediate carbonate content (+) have intermediate Mg and Ca values. Na content is low in all samples.

The values are characteristic for a fresh ground water system (pers. comm. Dr. C.A.J. Appelo). This does not necessarily imply a fresh water depositional environment, since the cation composition may have changed after the deposition. If the Na content had been high in some samples it would have indicated a salt water origin. Since the samples have low Na values it is impossible to differentiate on this basis between primary fresh water deposits and primary salt water deposits, in which the salt formation water was later replaced by fresh ground water. The deep decalcification in some members (Gilze, Turnhout, Rijkevorsel) points to intense percolation of ground water. It seems likely that the recent cation composition is different from the original one during deposition. Therefore, no conclusions can be drawn concerning the depositional environment based on the recent cation composition.

3.5.4 Deer antlers

During the last century several finds have been reported of deer antlers in the Campine Clay Formation (Rijkevorsel and Turnhout Members) in Belgium. They belong to the species *Eucladoceros tegulensis*, *E. falconeri* and *Cervus s.l. incertae sedis* (= *Cervus rhenanus*?) (Germonpré, 1983). Unfortunately the precise stratigraphic position of the finds is often unknown. One fragment of *Eucladoceros tegulensis* was found in the Turnhout Member. According to Germonpré (1983) the antlers are always well preserved. They do not show traces of alteration or abrasion. Therefore, the antlers probably occurred in situ in the Campine Clay Formation and they are not reworked from older deposits.

The Rijkevorsel and Turnhout Members are interpreted as landward, tidal flat and tidal litter zone deposits (§3.3.2 and §3.3.4). Since the antlers appear to occur in situ in the deposits, it is concluded that the deer probably lived or grazed in the tidal litter zones. They lost their antlers, which were subsequently buried by new sediment during spring tides. During later decalcification of the Campine Formation calcareous material disappeared, but the horny antlers (and an elephant tooth reported by Van Straelen, 1920) remained intact.

3.6 Discussion and summary of the sedimentary environments

In this paragraph, the sedimentological results and other evidence are summarized and evaluated, against the background of former ideas, concerning the depositional environments of the Early-Pleistocene deposits in The Netherlands and Belgium (see table 2.1).

The Rijkevorsel Member, which belongs to the Tegelen Formation and Campine Clay and Sand Formation, is characterized by regular and frequent alternations of sand and clay (lenticular and flaser bedding) in combination with bidirectional cross-bedding. These structures point to a tidal environment. The large-scale sedimentary sequence is often characterized by a coarsening-upward at the base of the member, followed by a fining-upward sequence. Since occasionally continental (peat) deposits are present below/at the base of the Rijkevorsel Member, the coarsening-up is interpreted as the drowning of the area. The most sandy part in the middle of the Rijkevorsel Member reflects the maximal tidal influence during the transgression. The fining-upward at the top of the Rijkevorsel Member indicates inshore silting of the tidal area, as offshore progradation would, on the contrary, be reflected by a coarsening-upward sequence. The general clayeyness of the

Rijkevorsel Member is explained by low energetic conditions and slow migration of the tidal channels, which is characteristic for landward (distal) parts of tidal environments. Salinity of the paleoenvironment is difficult to establish, since molluscs and diatoms are absent. However, bioturbation is scarce, which points to a limited biological activity, probably due to a low salinity. Tidal range was estimated between 0.95 and 2.1 m, uncorrected for compaction.

To the west grain-size increases in the Hoogerheide Member (Tegelen Formation), which is characterized by large-scale cross-bedding, flaser bedding and herringbone cross-bedding. The coarser grain-size and smaller thickness of the clay-layers are explained by active tidal channel migration. Hummocky cross-bedding at the top of the Hoogerheide Member points to wave activity. These characteristics indicate a more seaward (proximal), inshore, tidal environment with respect to the Rijkevorsel Member.

In the southeastern part of the investigation area around Beerse the Rijkevorsel Member is covered by the Beerse Member (Campine Clay and Sand Formation, Tegelen Formation). In The Netherlands the Beerse sands are always absent, due to erosion prior to deposition of the Turnhout Member. Sedimentary structures are dominated by dry eolian, parallel horizontal and low-angle cross-bedding, crinkly wet eolian adhesion bedding and contorted bedding. Superficial runoff was locally present. There is a fair resemblance to the bedding types distinguished by Ruegg (1983) and Schwan (1986) in Weichselian eolian sand-sheets. The periglacial structures (frost cracks, ice-wedge casts, cryoturbations) indicate cold climatic conditions with a mean annual temperature of approximately -5°C during the deposition of the eolian sand-sheet deposits of the Beerse Member.

The Beerse Member is covered by the Turnhout Member (Campine Clay and Sand Formation, Tegelen Formation). The Turnhout Member has many sedimentary characteristics in common with the Rijkevorsel Member. The regular alternations of sand and clay, the bidirectional cross-bedding, the fining-upward sequences, the general clayeyness of the sediment, the absence of bioturbations and the presence of pyrite point to landward (distal), inshore tidal, fresh to brackish environments. A tidal range of 1.05 m was estimated at Meerle. Tidal litter zones, characterized by *Chenopodiaceae* species, occurred at the southern fringe of the tidal environment. The Turnhout Member can easily be correlated with the coarser-grained Woensdrecht Member (Tegelen Formation) in the west. The larger grain-size, the abundance of clay-pebbles, the large-scale bidirectional cross-bedding with neap-spring-neap tidal cycles, the wave-induced coarsening-up at the top of tidal flat deposits and the presence of faint bioturbations are indications for a seaward (proximal), inshore (estuarine) tidal, brackish environment. Tidal range was more than 1.2 to 1.7 m.

The depositional environments of the Rijkevorsel and Turnhout Members are essentially in agreement with previous Belgian investigations. Dricot (1961), De Ploey (1961) and Paepe and Vanhoorne (1970) all stressed the tidal character and interpreted the sediments as tidal flat and salt-marsh deposits. They probably over estimated the salinity of the environment, since the sediments were described as salt-marsh ("schor") deposits. In our opinion, however, the upper parts of the Rijkevorsel and Turnhout Member in Belgium have been formed in tidal litter zones or brackish to fresh water marshes in which *Typha* was important. In The Netherlands the Rijkevorsel and Turnhout Members (Tegelen Formation) have been interpreted as fluviatile deposits of the Rhine and the Meuse (Doppert and Zonneveld, 1955; Van Dorsser, 1956; Van Voorthuysen, 1957; Zagwijn and Van Staalduinen, 1975), probably

because the sediments had to be studied in borings and did not contain marine shells and diatoms. Only when marine molluscs were found in the Rijkvorsel Member around Breda, was the tidal character recognised and the sediment incorporated into the marine, shell-bearing Maassluis Formation (Zagwijn and Van Staalduinen, 1975). The sandy deposits of the Woensdrecht Member in western Noord-Brabant have been misinterpreted as a braided or meandering river deposit (Van Dorsser, 1956; Van Voorthuysen, 1957: Halsteren Beds; Van Meurs, unpubl.; Damoiseaux, 1982), probably because of the dominant, westnorthwest directed stream direction, in the estuarine deposits. The stable to mixed heavy mineral association is not an indication of fluvial deposition by the Meuse (Van Dorsser, 1956), since it can be explained by estuarine processes (§5.4.4).

Up till now sedimentological information concerning the Kedichem Formation was scarce. A fluviatile, fluvio-periglacial and eolian origin had been proposed, but no details were given (Zonneveld, 1958; Zagwijn and Van Staalduinen, 1975; Bisschops et al., 1985). The recent investigations reveal that the Gilze Member, which is part of the Kedichem Formation, is a complex unit, which has been formed in several depositional environments. The rapid alternations of sand, loam and peat-layers in the lower unit (Appelenberg Sands) may be attributed to a fluvial environment with small river channels, overbank deposits, backswamps and lakes. The large-scale, fining-upward sequences with extensive clay-layers at the top of the second unit (Gilze Clay) are interpreted as floodplain deposits of a meandering river, consisting of channel and backswamp sediments. The coarser grained upper unit (Alphen Sands) with large-scale, trough shaped, cut-and-fill structures is interpreted as a sandy, braided river deposit (or deposits of ephemeral streams), which is in agreement with Vandenberghe and Krook (1981) and Vandenberghe et al. (1986). The Gilze Member occurs close to the surface west of the Gilze-Rijen and Hooze Mierde fault. It is correlated with the St. Lenaarts Formation at Ravels on the Campine microcuesta in Belgium (De Ploey, 1961). The large-scale, fluvial character of the sediments was underestimated by De Ploey, when he interpreted the St. Lenaarts Formation as an eolian deposit reworked by fluvial processes. The Bavel Member (Kedichem Formation) was deposited by a large meandering river in a more than 10 m deep channel, incised into the Gilze Member. Thick, massive and laminated, calcareous clays were interpreted as the infilling of meander cut-offs. Large-scale, trough cross-bedded sand was deposited in fluvial channels by southwesterly directed currents (Zagwijn and De Jong, 1984: Bavel I, Ia). The younger formations, belonging to the Middle- and Late-Pleistocene, are not discussed here (see §3.3.9).